Watercourse contamination in post-bushfire watersheds:
A study on trace metal and polycyclic aromatic hydrocarbon (PAH) mobilisation in Cudlee Creek

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TABLE OF CONTENTS

ABSTRACT

In the midst of Australia's 'Black Summer' of bushfires in 2019-20, South Australia experienced numerous days of extreme heat, drying out vegetation and steadily increasing tinderbox conditions. On 20 December 2019, a day of catastrophic fire danger, a pine tree in the Adelaide Hills fell and hit a powerline, sparking a blaze which by the end of the day had torn through forest, orchards, vineyards, pasture and homes. By the end of the day the Cudlee Creek bushfire had torn through over 23,000 ha in the upper reaches of the River Torrens, Onkaparinga River and Bremer River catchments.

The impact on watercourses of contaminants generated and remobilised through bushfire remains an under-investigated area of environmental research, which is of concern in the Australian context, where climate change may mean that 'Black Summers' occur more frequently. In forest catchments like in the Cudlee Creek bushfire area, vegetation acts as a stabilising force for soils, and acts to filter excessive or undesirable nutrients before they enter sensitive watercourse environment. However, bushfires in these areas turn the benefits of forest catchments around; vegetation becomes fuel, creating carcinogenic polycyclic aromatic hydrocarbons (PAHs) from incomplete combustion which can adsorb to ash and be distributed widely, while contaminants held in situ vegetation are remobilised. Runoff of sediments containing these contaminants poses a threat to the health of the watercourses and to the people who rely on them.

This research investigated the water courses in the Cudlee Creek bushfire to determine if concentrations of trace metals and PAHs were affected by the bushfire event. As an extension to that aim, this research also investigated whether the Cudlee Creek bushfire affected water safety in the Adelaide Hills region. The use of Graphical Information Systems (GIS) software was used to investigate the characteristics of the catchments and assess the severity of the burning, from which a sampling plan of watercourses was devised. Over the course of six monitoring events, samples of surface water were collected to test for metal and PAH concentrations in areas of the River Torrens and Onkaparinga River catchments. A photo set of all the sampling locations was also used to create a visual log of the area and support the quantitative research by assessing the health of the riparian vegetation along the watercourses.

Testing of the samples collected in this area found no strong evidence of increased concentrations of metals attributable to the Cudlee Creek bushfire. No PAHs were detected in the area, but limits in PAH testing, and the evidence of low metal mobilisation coupled with the strong recovery of riparian vegetation in the Cudlee Creek bushfire area suggested that there were no ongoing contaminant effects by PAHs.

This research acts as a solid basis of knowledge that will act to further develop the understanding of the relationship between metals and PAHs, and the impact of bushfire events on their concentrations in the watercourse. This research represents a base from which further research into the sensitivities of waterbodies in post-fire forest catchments can be developed and adapted.

Key Words: trace metals, polycyclic aromatic hydrocarbons (PAH), bushfire, watercourse contamination, contaminant mobilisation, forest catchment

DECLARATION

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

Signed....Jack Luxton............................

Date.......28/05/2021................................

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LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

Abbreviation	Definition
AAS	atomic absorption spectrometer
ADWG	Australian Drinking Water Guidelines
BAIS2	Burned Area Index for Sentinel-2
CCFR	Cudlee Creek Forest Reserve
CCWS	Cudlee Creek Water Sampling
DEW	Department for Environment and Water
DEWNR	Department of Environment, Water and Natural Resources
dl	detection limit
DPTI	Department of Planning, Transport and Infrastructure
ESA	European Space Agency
EPA (SA)	Environment Protection Authority (South Australia)
MSI	multi-spectral instrument
NBR	Normalised Burn Ratio
nd	not detected
NDVI	Normalised Difference Vegetation Index
NIR	near infrared
PAH	polycyclic aromatic hydrocarbon/polyaromatic hydrocarbon
PCDD	polychlorinated dibenzo-ρ-dioxins
PCDF	polychlorinated dibenzofurans
SWIR	short-wave infrared
VSPI	Vegetation Structure Perpendicular Index
∆NBR (or dNBR)	delta/difference Normalised Burn Ratio

1. INTRODUCTION

1.1. Research Rationale

The destructive power of bushfires is a familiar theme in Australia, where hot, dry summers have led to significant events occurring with regularity. Between November and March 2019-2020, bushfires throughout much of southern Australia caused the largest and most severe burning event in the country's recorded history, the period becoming known as 'Black Summer' (Davey & Sarre 2020; Deb et al. 2020). This intense and widespread burning caused the loss of 33 lives, many houses and properties, extensive tracts of native vegetation (Davey & Sarre 2020) and an estimated 500 million to 1.5 billion animals (van Oldenborgh et al. 2021), with the effects of the bushfire expected to cause over $100 billion of economic loss to the Australian economy (Read & Denniss 2020). Whilst the immediate impact of the bushfires and the associated imagery were devastating, some other effects of bushfires were not immediately obvious, with the impact on the ecosystem taking time. One such concern is the effect that bushfires have on waterbodies, particularly those that are relied upon for potable human use.

Waterbodies are vulnerable to contaminant entry through mobilisation of sediments due to rainfall-runoff or elements within groundwater leaching into them (Smith et al. 2011b). Forest watersheds, where the area contributing to the watercourse has significant vegetation (particularly in riparian zones) act to protect the watercourses (Abraham, Dowling & Florentine 2017), as this vegetation can act as a sink for trace metals in the soil, absorbing them and holding them in place through root stock (Mok et al. 2013). Additionally, the vegetation roots hold soil in place, meaning that soil with contaminants within it is less likely to be mobilised with rainfall-runoff (Shakesby & Doerr 2006). This is beneficial to the quality of runoff that enters the watercourse, and is part of why watersheds such as this account for nearly a third of the world's superficial potable water supply (Smith et al. 2011b). However, these areas are inherently vulnerable to bushfires, as this vegetation can act as fuel for these events. Bushfires in forest catchments destroy this ecological contaminant sink, releasing contaminants such as trace metals back into the ecosystem (Abraham, Dowling & Florentine 2017), as well as creating new ones such as polycyclic aromatic hydrocarbons (PAHs) as a result of incomplete combustion (Freeman & Cattell 1990).

Burnt vegetative material in the form of ash can contain and adsorb these contaminants, which can move with wind and be deposited over significant distances (Santin et al. 2015). Fire also influences the geomorphology of these areas, by drying out and destroying root systems, reducing the stability of soils. These soils become at risk to land-slips, and present the danger of contaminants held *in situ* being able to remobilise (Smith et al. 2011b; White et al. 2006). Rainfall-runoff in these forest watersheds that have been affected by bushfire have the potential to move the contaminants within ash and soils into the watercourse, which can affect the water quality for local biota and present pathways to risk of human health (Smith et al. 2011b).

The risk of these conditions conducive to extreme bushfire has become more frequent due to climate change (Sanderson & Fisher 2020; van Oldenborgh et al. 2021). As a result, water supply networks may be put under even greater stress, particularly given the reliance in many parts of the world on forest watersheds for potable water. While previous studies have investigated various water quality parameters in relation to bushfire, the danger posed by trace metals and PAHs has received relatively little study in the Australian context. Such an avenue merited further study, given the recurring danger that bushfires pose to Australia, and reliance on forest watersheds for potable water in much of south-eastern Australia (Smith et al. 2011b).

While devastating, the Australian bushfires of 2019-2020 presented an opportunity for study, and an opportunity to learn about the risks future bushfire events may pose. This thesis investigated the aftermath of the Cudlee Creek bushfire in the Adelaide Hills, which encompassed an area in the upper reaches of the Torrens, Onkaparinga, and Bremer River catchments. Samples were collected from the superficial watercourses in the area affected by bushfire over a period over ten months, with laboratory analysis to determine if there was the presence of trace metals and PAHs at specified locations. A photographic set of the sample sites was also kept to monitor the health of the riparian vegetation of the watercourse in the period subsequent to any contaminant mobilisation due to the bushfire. Using this information, this research aimed to contribute broadly to further understanding of the impact of bushfire on watercourses in the Australian context, and specifically to determine if there were any ongoing impacts in the Cudlee Creek region.

1.2. Preliminary Research Outline

In order to appropriately design the study of metals and PAHs in the Cudlee Creek bushfires, preliminary research was conducted to investigate two important aspects that informed the design and structure of research in this thesis. The first aspect of the research was to investigate the physical mechanisms of bushfire that contribute to the mobilisation of contaminants. For this purpose a literature review was conducted, which investigated the relationship between the broad scale relationship between climate change and bushfires to the local influence of bushfires on contaminant mobilisation. Included in this section was a detailed review of literature outlining the health effects of metals and PAHs in water, and the way in which bushfire can mobilise these contaminants. This review of contaminants and their mobilisation into water sources was used in the design of the research. Similar studies into contaminants in post-bushfire watersheds were used to understand what results may be expected, and to support the methodological choices in the design of this research.

The second aspect of the preliminary research related to the Adelaide Hills region affected by the Cudlee Creek bushfire. The investigation provided the context of the region and how the bushfire developed. In addition, the characteristics of the area affected by the bushfire were investigated using Graphical Information System (GIS) mapping data available from the South Australia government. The purpose of this mapping was to gain an understanding of the geography and the surface hydro-geography, as well as the land cover in the region. This analysis informed the practical design of the research, and provided context to the results obtained relating to the different characteristics between catchment areas.

1.3. Literature Review

1.3.1. Climate Change and Bushfires

A growing body of literature has examined the relationship between anthropogenic climate change and the increase in extreme bushfire[1] events (Di Virgilio et al. 2019; Maco et al. 2018; Sanderson & Fisher 2020; van Oldenborgh et al. 2021). An increase in extreme weather events is one of the predicted results of climate change, with resultant events such as fire and flood expected to increase in frequency and intensity (Maco et al. 2018). As evidenced by the catastrophic bushfires that Australia experienced in the summer of 2019-20, the future risk of extreme bushfire events cannot be overstated (Sanderson & Fisher 2020). Directly linking such events to climate change has proven difficult given the variety of factors that influence the conditions that cause bushfire and the uncertainty in current climate modelling (van Oldenborgh et al. 2021); however many localised factors influenced by the extension of dry seasons and elevated temperatures have been shown to be correlated with the catastrophic bushfires of 2019-2020 in Australia (Deb et al. 2020; van Oldenborgh et al. 2021). Increased days of extreme heat present greater time and opportunity for fuel materials to dry out, and for incidents sparking bushfires to occur (Di Virgilio et al. 2019).

Any change in frequency and intensity of bushfires has implications for quality and safety of water in the fire affected watershed (Smith et al. 2011a). Bushfires can affect contaminant toxicity and transportation pathways, which can cause mobilisation into watercourses and disruption of the ecosystem (Smith et al. 2011a; Son, Kim & Carlson 2015). Fires in particular present risk in forest catchments, where contaminants previously *in situ* or generated through combustion may be mobilised into watercourses (Smith et al. 2011b; Wade et al. 2013).

1.3.2. Bushfire in Forest Watersheds

Forest watersheds serve as a potable water source for nearly a third of the world's largest cities (Smith et al. 2011b), and the ongoing health of the watercourse is vital for these areas. Forest watersheds provide many services to water supply, particularly with vegetation acting as a filter for runoff entering into watercourses (Abraham, Dowling & Florentine 2017). However, this vegetation also means these areas are vulnerable to bushfire, given the presence of the fuel necessary to feed these events. When bushfires burn through these areas, it can take significant amounts of time for water yield to recover while revegetation occurs (White et al. 2006) and previously filtered contaminants mobilised within these areas have the potential to compromise water safety (Smith et al. 2011a). Additionally, new contaminants (such as PAHs) are generated in the combustion process during bushfires, presenting additional risks to the health of the watercourses, the surrounding biota and ultimately to humans (Nunes et al. 2018).

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[1] For the purposes of this thesis, the common Australian term "bushfire" is used to refer to unplanned burning of vegetation, including forest fire and grass fire. Other terms used in the literature, particularly "wildfire", are considered to refer to similar phenomenon (Llyod 2018; Rural and Land Management Group 2012).

1.3.3. Contaminant Mobilisation by Bushfire

The effect of bushfire on a range of contaminants and water quality parameters has been investigated previously, with metals (Sequeira et al. 2020; Smith et al. 2011b), nitrogen and phosphorous loads (Lane et al. 2008; Son, Kim & Carlson 2015), total dissolved solids and turbidity (Wade et al. 2013; White et al. 2006) and carcinogens such as PAHs (Gabos et al. 2001; Olivella et al. 2006) and polychlorinated dibenzodioxins and dibenzofurans (PCDD/Fs) (Gabos et al. 2001) all being considered. The method in which these contaminants are released varies, some released into the atmosphere as vapour and some in solids through ash or into soils. To determine which contaminants are relevant, it is important to define contaminants in the context of the end-use of the water asset at risk (Nunes et al. 2018). In consideration of the risks to human health in water sources, the presence of trace metals and PAHs are most relevant in terms of potential harm and likelihood. The pathway for this material entering into watercourses is driven significantly by the effect that bushfire has on the soil.

In intense bushfires, heating of the soil causes the nature of soils to change, becoming hydrophobic and changing the stability of the soil components (Shakesby & Doerr 2006). Vegetation losses can cause loss of structure within the soil causing it to loosen, and the loss of riparian vegetation to bushfires removes natural barriers which reduce runoff and sediments entering waterbodies (Smith et al. 2011a). Runoff from subsequent rainfall can then mobilise loosened soil and ash generated by bushfire events into watercourses (Abraham, Dowling & Florentine 2017; Nunes et al. 2018; Shakesby & Doerr 2006). Ash material containing contaminants similarly is transported via runoff, as well as by wind erosion due to low density (Harper et al. 2019). The method of transportation of ash and soil varies depending on geography, with saturation based mass movement or runoff debris flow occurring in different locations (Nunes et al. 2018), with debris flow runoff observed to be prevalent in catchments in south-eastern Australia (Nyman et al. 2011).

1.3.4. Trace Metals in Watercourses

Many soils contain trace metals naturally in low level trace amounts; however, mining, agriculture fertiliser and pesticide and air-borne particles resulting from anthropogenic combustion has caused metals to be distributed into the environment where they can concentrate to higher levels (Wuana & Okieimen 2011).The trace metals typically associated with contaminant transport are outlined in Table 1, as these metals were seen to have the greatest potential for harm to biota and humans (Abraham, Dowling & Florentine 2017). The Australian Drinking Water Guidelines (ADWG) set a health limit for these metals, a safety based measure of the limit of contaminant concentration that research suggests does not pose a significant health risk over the course of a human lifespan. The ADWG also set an aesthetic limit in certain cases where contaminant concentrations are safe for consumption, but the characteristics of the water become undesirable to drink for the consumer (NHMRC & NRMMC 2021).

Table 1: Trace Metals of Most Concern with Australian Drinking Water Guideline Values (ADWG) (adapted from NHMRC and NRMMC (2021))

Trace metals of most concern	Australian Drinking Water Guideline Values	
	Health Limit (µg/L)	Aesthetic Limit (µg/L)
Arsenic (metalloid)	10	-
Cadmium (Cd)	2	-
Copper (Cu)	2000	1000
Chromium (Cr)	50	-
Lead (Pb)	10	-
Manganese (Mn)	500	100
Mercury (Hg)	1	-
Nickel (Ni)	20	-
Zinc (Zn)	-	3000

The ADWG were used as the health limit for this report, as the primary concern regarding the contaminants was impacts to human health. In most cases these were the most sensitive contaminants concentration limits in the literature; however it was noted that copper concentrations health limits for aquatic ecosystems and in primary industries were lower than the ADWG, at around 5 µg/L, (ANZECC & ARMCANZ 2000).

Trace metals pose a multitude of health risks in humans and wildlife, with prolonged exposure potentially leading to toxic, neurotoxic and carcinogenic properties depending on the properties of the metal (Smith et al. 2011b). This can be particularly hazardous if metals enter the water supply and are ingested. Vegetation has an important role in preventing these trace metals entering watercourses, as it can act as a sink, absorbing and keeping them *in situ* (Mok et al. 2013). This phytoextraction occurs when metal ions from the soil dissolve and are absorbed by plant roots, which are then translocated and stored within the body of the plant above the soil layer; if the plant is metal-tolerant, significant concentrations of metals can be fixed this way (Wuana & Okieimen 2011). The phytoextraction and soil stability provided by vegetation reduces the impact of trace metals entering into other areas of the ecosystem, which may otherwise affect aquatic biota (Harper et al. 2019).

The mobilisation effects of bushfire are twofold, with metals being transported through both wind and water erosion of sediments. Metals that are absorbed and within the structure of the plants themselves are remobilised in the ash resulting from burning (Campos et al. 2015; Smith et al. 2011b), with light ash able to be eroded by wind and deposited elsewhere in the catchment (Santin et al. 2015). Bushfire can also reduce the stability of topsoil due to loss of root binding, meaning soils (and deposited ash) can be more easily moved by rainfall runoff (Santin et al. 2015; Shakesby & Doerr 2006). In addition, bushfires can mobilise anthropogenic sources of metals, where the burning of common structures such as fence posts treated with compounds such as copper chrome arsenate (CCA) can release arsenic into the environment (Spinks et al. 2006).

The increased transport of metals presents an issue for the forest catchments, where increased movement with rainfall runoff implicitly raises the chance of the contaminated soils reaching watercourses. The testing for metals in watercourses within catchments affected by fire has been explored widely in the literature. The trace metals tested for in the literature varied, however in a meta-analysis of these studies it was observed that testing for copper, lead and zinc was most prevalent (Smith et al. 2011b). Elevated (although not necessarily hazardous) levels of a variety of metals were observed across these studies, with evidence of re-mobilisation of mercury and arsenic of most concern (Abraham, Dowling & Florentine 2017). The ability of plants to absorb metals can vary (Mok et al. 2013), hence metals mobilised in bushfire events may depend on the type of vegetative cover in the area. For example, mercury concentrations in post bushfire soils of eucalypt dominant areas were shown to be twice that of pine forest areas (Campos et al. 2015). Research in the Australian context remains limited (Smith et al. 2011a), however research has indicated a relationship between the bushfires and metal mobilisation (Wade et al. 2013), however the scale of metals mobilisation in bushfire ash has not replicated results seen elsewhere in the world (Santin et al. 2015).

1.3.5. Polycyclic Aromatic Hydrocarbons in Watercourses

PAHs are a group of organic compounds are a group of compounds formed as a by-product of incomplete combustion (Freeman & Cattell 1990; Mansilha et al. 2019). They are identified by a molecular structure that includes a minimum of two aromatic rings (Ravindra, Sokhi & Van Grieken 2008), and with over 100 different compounds included within this classification, can vary in size and characteristics significantly (Freeman & Cattell 1990). The health risk posed by these PAHs differs, with Table 2 listing those that are commonly tested for, the bulk of which were identified to be of most concern by the United States Environmental Protection Agency due to their potential harm, exposure pathways and prevalence (Keith 2014; Mansilha et al. 2019; Ravindra, Sokhi & Van Grieken 2008). Due to insufficient data regarding safe limits of PAHs in soil and water, the ADWG do not set explicit limits for any compound except Benzo[a]pyrene (BaP), with a health limit of 0.01 µg/L. Instead, the estimated relative carcinogenic potency of other PAHs relative to BaP was presented, as shown in Table 2, with BaP considered unity. These relative potency values give the estimated order of magnitude of the safe limits for other PAHs, useful where a mixture of different PAHs are present (NHMRC & NRMMC 2021).

Table 2: PAHs of most concern relative potency to BaP (adapted from NHMRC and NRMMC (2021))

PAHs of most concern	Potency relative to BaP
Acenaphthene (Ace)	<0.01
Acenaphthylene (Acy)	<0.01
Anthracene (Ant)	<0.01
Benz[a]anthracene (BaA)	0.1
Benzo[b]fluoranthene (BbF)	0.1
Benzo[j]fluoranthene (BjF)	0.1
Benzo[k]fluoranthene (BkF)	0.1
Benzo[a]pyrene (BaP)	1
Benzo[e]pyrene (BeP)	<0.01
Benzo[ghi]perylene (BghiP)	0.01
Chrysene (Chr)	0.01
Dibenz[a,h]anthracene (DahA)	1-5
Fluoranthene (Flt)	<0.01
Fluorene (Flu)	<0.01
Indeno[1,2,3-c,d]pyrene (Ind)	0.1
Naphthalene (Nap)	<0.01
Phenanthrene (Phe)	<0.01
Pyrene (Pyr)	<0.01

The carcinogenic effects of the by-products of combustion have been recognised for over 200 years, with the mutagenic properties of PAHs responsible (Freeman & Cattell 1990). Study of the pathways in which humans are exposed to PAHs has largely focussed on anthropogenic sources of incomplete combustion, such as the burning of fossil fuels in transport, industry and energy production, or the use of gas and wood in domestic settings (Ravindra, Sokhi & Van Grieken 2008). Only relatively recently have natural sources of PAHs been considered as potentially harmful to human health.

The focus on anthropogenic sources of PAHs has occurred due to the difference in the way exposure to natural sources of PAHs occurs. Natural PAH sources consist of incomplete combustion during bushfire or volcanic events, with their sporadic nature suggesting they are of less immediate concern than the ongoing exposure of anthropogenic sources (Srogi 2007). However, with efforts to reduce the emission of PAHs from anthropogenic sources, it is thought that the relative impact of natural sources may be increasing (Wang et al. 2016). It is also important to note that natural PAH events also have the potential to have very significant effects over short timeframes when they do occur (Freeman & Cattell 1990).

The nature of the PAHs released during bushfire events depends significantly upon the intensity of the fire and available fuel sources. Due to PAHs with low molecular weight having a low vapour pressure, most PAHs released in combustion enter the atmosphere as vapour, with a number of studies completed on the human health risk due to these pathways (Ravindra, Sokhi & Van Grieken 2008; Wang et al. 2016). PAH molecules may also adsorb to small dust particles, allowing them to enter local sediments or attach to ash generated by bushfires (Spinks et al. 2006). Ash particles can quickly be mobilised by wind and runoff, meaning that PAHs attached to these particles can be distributed widely in the ecosystem (Bodí et al. 2014). The deposition and movement of PAHs within forest watersheds thus presents an additional pathway of risk to human health to that of vapour (NHMRC & NRMMC 2021).

Study of sediments indicated that PAH concentrations increased in the immediate aftermath of bushfires (Gabos et al. 2001), with concentrations of PAHs higher in deposited ash than the topsoil underneath (Campos et al. 2019). The sensitivity of the composition and concentrations of PAHs in sediments relative to fire intensity has not been established in the literature. Various studies have observed greater PAH generation in more severely burnt areas (Kim, Choi & Chang 2011), greater PAH generation in the moderately burnt areas (Chen et al. 2018) and no significant difference between severely or moderately burnt areas (Campos et al. 2019). The type of vegetation burnt does appear to influence the concentration of PAHs generated, with pine plantation concentrations higher than those in eucalypt areas (Campos et al. 2019). Sediment PAH concentrations in the post-fire environment was observed to decrease significantly (particularly for lighter compounds) over the following months (Campos et al. 2019; Kim, Choi & Chang 2011). This change may be attributable to a number of processes; PAHs in soils can vaporise or degrade under photolysis (El-Saeid et al. 2015; Kim, Choi & Chang 2011), or leach further into soils and the water table (Mansilha et al. 2014). Transport by overland flow runoff is also a significant component of the reduction in PAH levels (Smith et al. 2011b; Vergnoux et al. 2011), which suggests that rainfall events subsequent to fire events have the effect of moving the PAHs within these sediments into watercourses.

PAHs are relatively insoluble in water, with insolubility increasing as the number of aromatic rings increase (Achten & Andersson 2015). This has resulted in less studies directed at understanding the impact of PAHs in watercourses and water quality, as noted by the lack of safe ADWG established (NHMRC & NRMMC 2021). However, recent studies have shown that there is some level of increased PAH concentration subsequent to bushfires. Mansilha et al. (2019) found that PAHs in Portuguese forest catchments exceeded European Union (EU) water quality standards for BbF, BkF, BghiP and Ind in the aftermath of fires in 2013, where concentrations peaked in sampling conducted 5 months post-fire. A similar study by Oliveira et al. (2017) in Catalonia did not find any results above safe drinking levels, but did find evidence that seasonal variation in streamflow can alter these concentrations. Passive sampling in streams after bushfires has also been conducted in Australia to assess toxicity to local biota (Schafer et al. 2010). Elevated levels of PAHs have also been found in the groundwater of bushfire affected areas, which indicated that the superficial aquifer can be affected by leaching of PAHs in soils (Mansilha et al. 2014).

Research into the sensitivity of potable water supply based on these watercourses was scant, however the effect on water storage has also been conducted in the Australian context, with Spinks et al. (2006) investigating PAH concentrations in private water tanks after bushfire events.

This study found that the ash fall on roofs did not significantly affect the PAH concentration in rainwater subsequently collected and stored in the water tanks, results supported by Ross et al. (2018).

This evidence suggested that there were established pathways for PAHs produced due to bushfire to make it into watercourses, and that that localised features such as vegetation type, seasonal variation in water flow and intensity of burning may play a factor. The degree of danger this poses to human health was also unclear, as while PAHs are known carcinogens, data are insufficient for safe limits in ADWG to be set (NHMRC & NRMMC 2021). This uncertainty suggested that understanding the PAH behaviour in the South Australian context was a knowledge gap worthy of investigation.

1.3.6. Methodology Review

An important part of the literature review was to analyse the methodological approach of the research regarding gathering data on bushfires and contaminant mobilisation. Studies of post-bushfire areas have been varied, depending on the scale of the assessment and objective of the research. Research relating bushfire to climate change relied upon climate models and weather indicators (Deb et al. 2020; van Oldenborgh et al. 2021), while synthesis reports used the prior research of others to conduct a meta-analysis that created a comprehensive and coherent base of knowledge (Abraham, Dowling & Florentine 2017; Smith et al. 2011b). A majority of the research relied upon the collection of physical samples for testing, although some used a combination of data collection and imagery to demonstrate bushfire impact (Joehnk et al. 2020; Mansilha et al. 2019) or to monitor bushfire recovery (EPA SA 2008).

Studies that analysed metals and PAHs in watercourses used a variety of approaches, although most often this involved the collection of sediments or superficial water samples from streams and springs deemed representative (Mansilha et al. 2019). The evidence was conflicted as to the timeframe of the peak PAH concentration post-fire. Olivella et al. (2006) found that the concentration peaked one month after fire, whereas there existed a delay in the peak concentration of bushfire related contaminants appearing in watercourses of multiple months for Mansilha et al. (2019). Such a delay could have occurred due to a lack of rainfall in warmer summer months when bushfires are more likely, meaning sufficient rainfall to generate runoff to move had not occurred. Regardless of the reason, the variability of catchment climate and geography meant it may take months or years for the full consequences of the fire event to be observed (Abraham, Dowling & Florentine 2017); this suggested that any study should be longitudinal to capture this change over time (Mansilha et al. 2019; Olivella et al. 2006; Sequeira et al. 2020).

The collection and testing of superficial water samples for metals was shown to be an effective and useful way of measuring the impact of contaminants associated with ash and sediment entering watercourse (Smith et al. 2011b). Where mentioned in the literature, procedures for sample collection and handling were based around ISO 5667 series of standards, and were effective at obtaining reliable results (Mansilha et al. 2019; Sequeira et al. 2020). Guidelines relevant in the local context regarding water and wastewater sampling were available from Environmental Protection Authority South Australia (EPA SA), which outlined procedures for best practice sampling methods based on AS/NZS 5667.6: 1998 standard (Duncan et al. 2007), which was itself an adaption of the ISO5667:6 standard (SA/SNZ 1998).

In the literature, PAH concentrations were typically tested by sediment analysis, as larger compounds were considered insoluble, with the targeted PAHs that did mobilise to do so due to adsorption to ash (Campos et al. 2019; Campos et al. 2015; Gabos et al. 2001; Kim, Choi & Chang 2011). Despite the literature focus on sediment analysis, Mansilha et al. (2019) demonstrated that PAH concentrations in water can exceed safe water limits, which suggested testing water samples for these substances was experimentally valid.

1.3.7. Literature Review Summary

This literature review has demonstrated how the global impacts of climate change can translate through to localised impacts on watercourses. It has demonstrated how bushfires present a real and increasing potential risk to water security in terms of mobilisation of metal and PAH, and identified the areas in which further knowledge could be built. This foundational understanding of how contaminants are mobilised and the potential threat they pose was thus applied to the context of the 2019 Cudlee Creek bushfire in South Australia.

1.4. Study in the Cudlee Creek Bushfire Area

1.4.1. Cudlee Creek Bushfire as a Case Study

The evidence from the literature review demonstrated that bushfires in forest catchments both created and mobilised contaminants which pose a potential threat to the safety of water sources, including rainwater tanks and watercourses. The potential for such mobilisation occurred in the Adelaide Hills December 2019, when a fire that ignited near the Cudlee Creek area led to extensive burning of the nearby forestry reserve and expanded southwards to a number of rural residential and agricultural areas. The Cudlee Creek bushfire (CCB) presented a significant risk of contamination due to the fact that many residents in the Adelaide Hills region retained dams for maintaining pastoral, agricultural or viticultural land (AMLRNRMB 2013), and/or rely on rainwater tanks as they are outside the traditional water infrastructure (Adelaide Hills Council 2019). In addition, a number of the watercourses in this area discharge into dams that regulate parts of the water supply for the Adelaide metropolitan region (AMLRNRMB 2013). Thus the Cudlee Creek bushfire presented a relevant case study that could act to provide evidence for the research gap identified in the literature review. The Cudlee Creek bushfire and the region affected were investigated to gain an understanding of the context in which the knowledge synthesised from the literature review could be applied.

1.4.2. Cudlee Creek Bushfire Background

The summer of 2019-2020 has become known as Australia's "Black Summer" of bushfires due to the sheer extent of damage to persons, property and land (Davey & Sarre 2020). While the most intense and extreme fire damage occurred in the south-east of Australia across New South Wales and Victoria (van Oldenborgh et al. 2021), South Australia also experienced significant bushfire damage to areas including the Adelaide Hills, Kangaroo Island and the Yorke Peninsula (Government of South Australia 2020).

The most serious of the fires in the Adelaide Hills was the Cudlee Creek bushfire, named after the small town in the Adelaide Hills near its ignition point. The fire occurred during a heatwave in mid-December 2020, where consecutive days of over 40°C had caused total fire bans and warning of catastrophic bushfire conditions (ABC 2019). Just after 9am on 20 December 2019, a pine tree in a plantation near Cudlee Creek fell and landed on the nearby power lines (Office of the Technical Regulator 2020). This incident sparked a blaze, with the initial fire so intense that it far exceeded the heat limit at which fire-fighting equipment can be effective (Government of South Australia 2020). Fuelled by extreme heat and high winds, by that evening the fire had burnt through 23,253ha of land between Cudlee Creek and Harrogate to the south-east, enveloping areas around Lobethal and Woodside along the way (Government of South Australia 2020).

The Cudlee Creek bushfire affected a number of Adelaide Hills communities, with 86 homes destroyed and one human life lost (Government of South Australia 2020). Large tracts of forestry and agricultural land were burnt, as well as nearly a third of the vineyards in the prominent wine region nearby (Hough, Herrman & Neindorf 2019). While the most damaging spread of the fire occurred within the first 24 hours, the bushfire was not contained for over a week. Containment occurred on 31 December, before it was controlled on 3 January 2020 and eventually declared safe on 22January 2020 (Government of South Australia 2020).

1.4.3. Cudlee Creek Bushfire Area Study Data

The extent of the Cudlee Creek bushfire was far greater than that of just the small town that lent it its name. To gain an understanding of the nature of the area that was affected by the Cudlee Creek bushfire, a Geographic Information Systems (GIS) review of the area was undertaken to investigate affected catchments and the component waterbodies and watercourses. The land use and land cover in the region was also considered relevant to gain an understanding of the composition of potential contaminants. Additionally, the topography of the region was used to understand how and when contaminants may be mobilised. This GIS review of the Cudlee Creek bushfire area used the various data listed in Table 3 with data processed in QGIS using the Coordinate Reference System of the Geocentric Datum of Australia 94 (GDA94).

Table 3: Datasets Used for Cudlee Creek Bushfire Preliminary Investigation

Feature	Data Name	Reference	Date Accessed
Catchments	WATER_Catchments_GDA94	DEW (2016a)	16/03/2020
Land Cover	LANDSCAPE_SA_ Landcover_2010_2015_ML_GDA94	DEW (2017)	15/05/2021
Land Use	LandUseGeneralised2019_ GDA94	DPTI (2020)	22/05/2021
Fire History	FIREMGT_BurnYear_GDA94	DEW (2020a)	01/07/2021
Last Fire	FIREMGT_LastFire_GDA94	DEW (2020b)	25/03/2020
Localities	Gazetter2012_SA_EAST	(Geoscience Australia 2013)	22/05/2021
Roads	Roads_GDA94	DPTI (2016)	25/03/2020
Topography	GEODATA TOPO 250K Series 3	Geoscience Australia (2006)	27/04/2020
Watercourses	TOPO_Watercourses_GDA94	DEW (2016b)	16/03/2020

1.4.4. Cudlee Creek Bushfire Area

The first stage of this investigation was to determine the extent of the Cudlee Creek bushfire. Fire scar mapping of major bushfires was available in shapefile format from the South Australian Department of Environment and Water (DEW 2020b). These data were used to show the extent of the area that was affected by the Cudlee Creek bushfire (Figure 1). The estimated area of this fire scar was 22,541 ha, which was approximately equivalent to the area stated by Government of South Australia (2020). Based on the initial ignition point specified in the report from the Office of the Technical Regulator (2020), it was apparent that the direction of bushfire movement was primarily to the east and south-east. A number of towns were within the fire area or just adjacent, including Cudlee Creek, Lobethal, Mount Torrens, Charleston, Woodside, Brukunga and Harrogate.

Historically, the area has generally experienced smaller localised bushfire events, with only a few comparable to the spatial scale of the Cudlee Creek bushfire (DEW 2020a). The Sampson Flat bushfire of 2015 to the north was spatially significant, however was largely bordered by the River Torrens, with only limited overlap with the Cudlee Creek bushfire area. The only other large fire event recorded that affected a spatially significant portion the Cudlee Creek area was during the Ash Wednesday bushfires in 1983, which affected the Torrens catchment around Cudlee Creek. The Onkaparinga and Bremer catchment regions affected by the Cudlee Creek bushfire have not been impacted by widespread fire events since spatial records were kept in 1934. This suggested that the area was not prone to widespread bushfires; however areas in the north of the catchment may possess greater fuel loads and geography that was conducive to bushfire propagation.

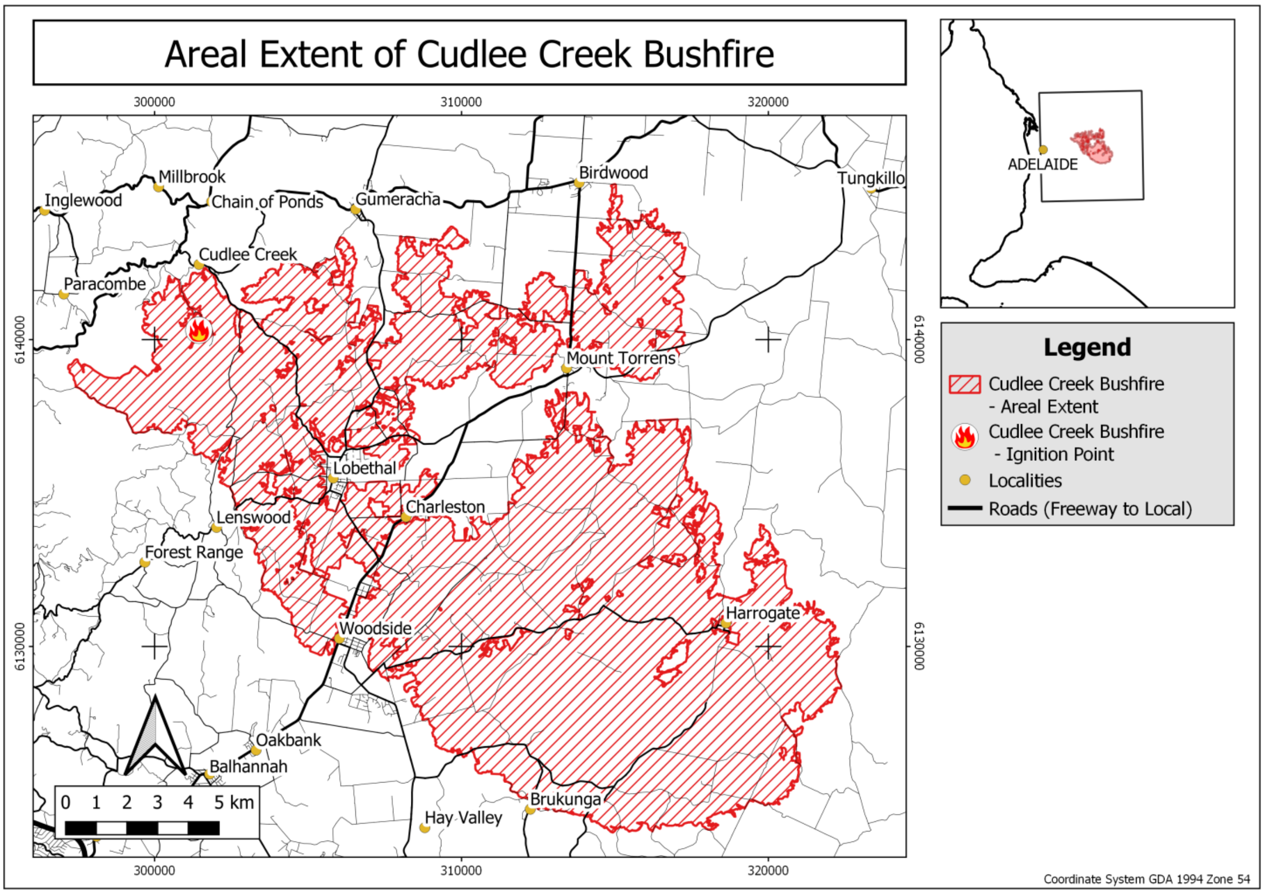


Figure 1: Map of the Areal Extent of the Cudlee Creek Bushfire

1.4.5. Geography of the Research Area

To understand the movement of the bushfire and to consider its impact on watercourses, it was pertinent to look at the catchments and their topography. Figure 2 shows that the bushfire was almost entirely contained within three catchments, for the River Torrens, Onkaparinga River and Bremer River. This effectively meant that any bushfire-affected soils mobilised by runoff would be contained within these catchments, with the water eventually entering into the watercourses on the map. Potential spread of PAHs adsorbed to ash particles through wind mobilisation was still possible; however for the purposes of this investigation these three catchments were considered the systems of interest.

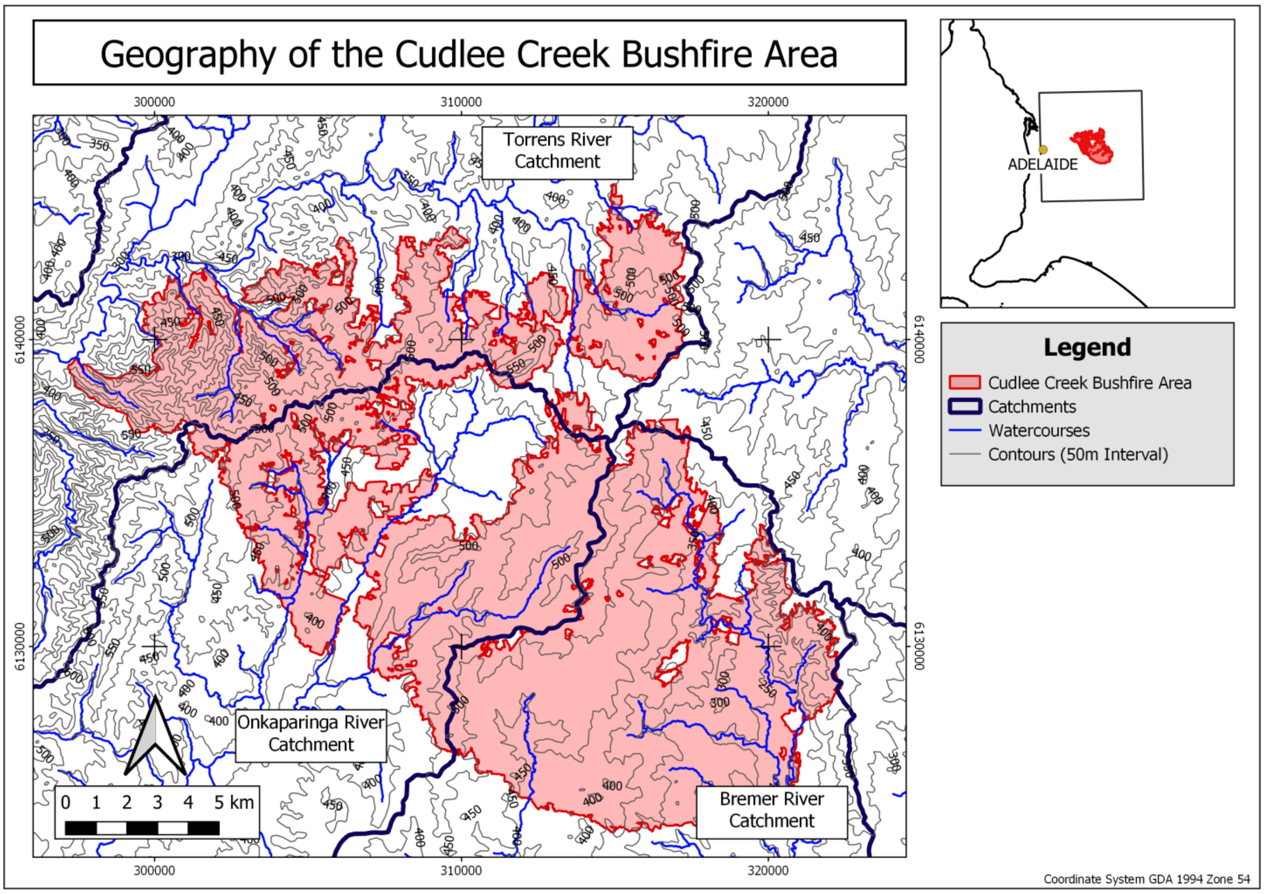


Figure 2: Map of the Geography of the Cudlee Creek Bushfire Area

Figure 2 shows that many of the tributaries in the upper reaches of these catchments were within the bushfire area. This suggested that if there were any contamination in these reaches, it could affect the length of the water course. These sections of the River Torrens and Onkaparinga River discharge into the Kangaroo Creek and Mt Bold reservoirs respectively, then ultimately continue to the ocean, whereas the Bremer River joins the Murray River.

Based on the contour lines in Figure 2, it was apparent that the ignition point occurred in a valley within an area with relatively steep slopes in comparison to the rest of the burnt area. This may explain the intensity of the initial ignition of the fire, as bushfires move quicker up inclines, due to heated air rising and drying fuel which is subsequently consumed as the fire moves up the hill (Sharples et al. 2016). The contour mapping also indicates that the land to the south-east of the ignition point was significantly flatter, which would suggest that there is more agricultural land in the Onkaparinga and Bremer River catchments.

In addition to the watercourses in Figure 2, there existed numerous waterbodies within the Cudlee Creek bushfire area that do not join the main catchment river. This included dams, lakes, and land subject to inundation and flooding, which are presented in Figure 3. This waterbody dataset from

DEW (2016c) provided these data as a shape file, with approximately 1270 of these waterbodies within the burnt area. The number of these locations would likely have been smaller at the time of the fire due to the dataset including intermittent ponding; however this number demonstrated that there are likely a significant number of residential dams in the affected area that may have been subjected to contaminated sediment runoff.

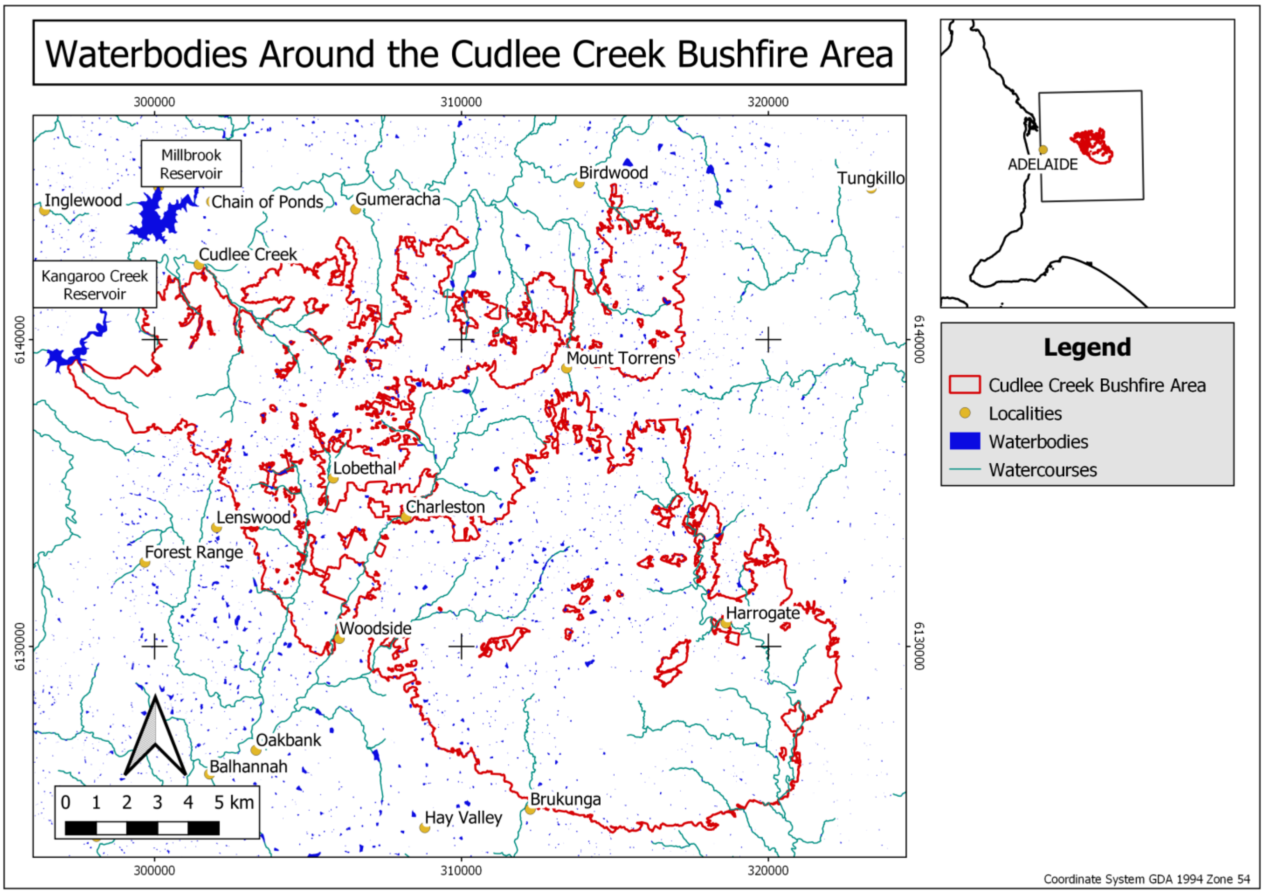


Figure 3: Map of Waterbodies around the Cudlee Creek Bushfire Area

1.4.6. Land Cover and Land Use in the Research Area

The large extent of the Cudlee Creek bushfire meant that while it started in a forested area, as it moved south-east it approached residential, viticultural, horticultural and agricultural areas. This meant that the fire encountered a range of different fuel types, including the denser native, forest and sparser low-lying grass in agricultural regions. The release of contaminants, particularly metals, in agricultural regions may be different than that of forest watersheds, partly due to the fact that these areas may be subject to the use of fertiliser and pesticides. As a result, accumulation in the soil of metals may result in different composition of sediments based on the land cover. Hence the land cover was considered, with satellite data used to show the proportion of land cover within the Cudlee Creek bushfire area in Figure 4. These data were produced by the Department of Environment, Water and Natural Resources (DEWNR) in South Australia (now DEW), and divided the imagery in 25x25 m pixels, with each pixel representing the likely dominant land cover at that location. Each pixel was classified into one of 17 categories relating to type of vegetation, agriculture or built environment at the location. This provided a good indication at catchment scale of the land cover in the area, where woody native vegetation was most prevalent in the north and west of the Cudlee Creek bushfire area near the ignition point of the fire, while more dryland agricultural land was found to the south east.

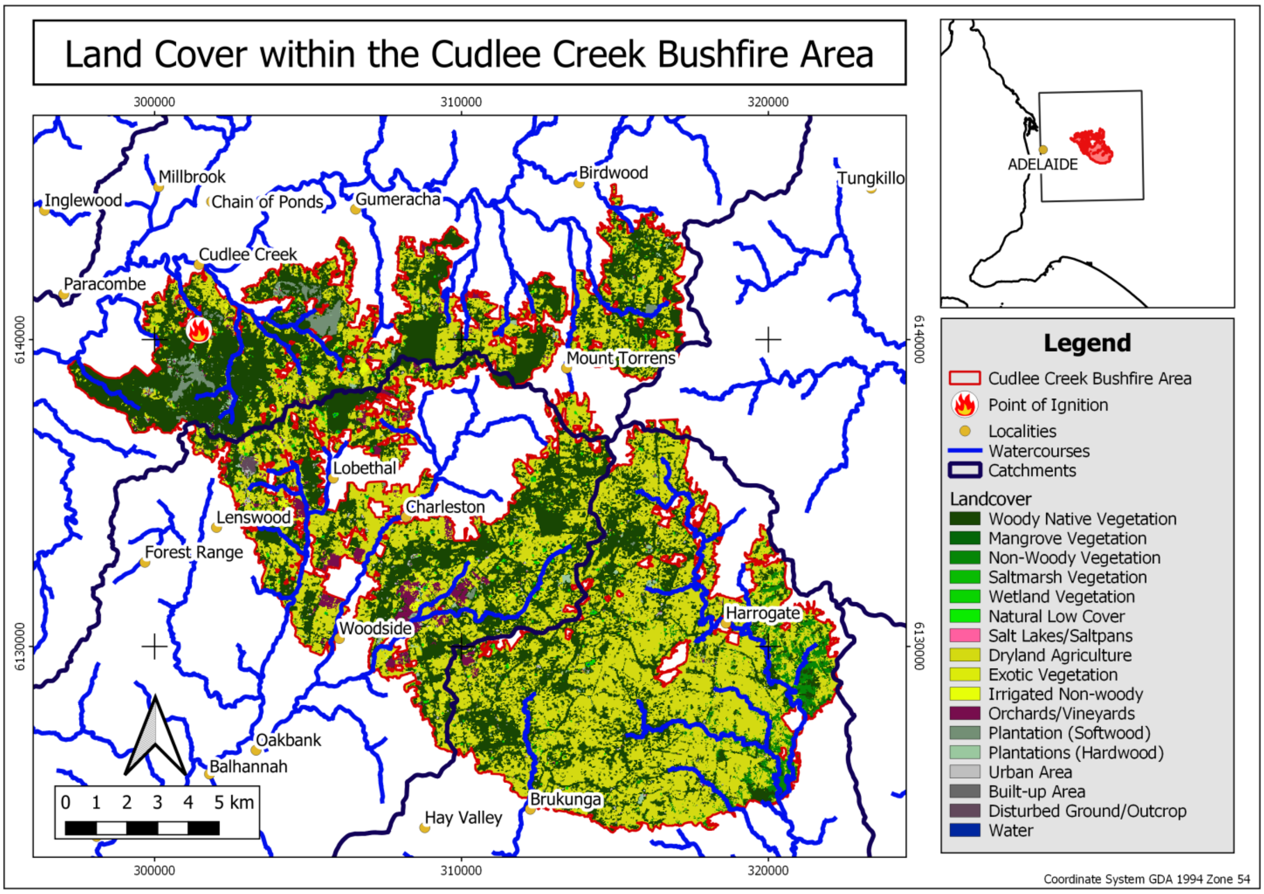


Figure 4: Map of Land Cover within the Cudlee Creek Bushfire Area

A summary of the pixel count for each land cover category within the raster of the Cudlee Creek bushfire area was conducted to estimate the relative proportion of each land cover in Table 4. This summary confirmed that the area has predominantly woody native vegetation and dryland agriculture surfaces, making up over 90% of the area combined. Small sections of softwood plantation, orchards and vineyards, and non-woody native vegetation made up a bulk of the remaining area. However, this analysis was also conducted on each of the major catchments within the bushfire area, which demonstrated that there was considerable variation at this level in the distribution of woody native vegetation and dryland agriculture between them. The distribution of land cover by percentage, shown in Table 4, also supported the observation that the northern and western areas of the bushfire, predominantly within the River Torrens catchment, possess significantly more woody native vegetation.

The River Torrens catchment had nearly twice the woody native vegetation present than the Bremer River catchment to the south-east; however, this ratio was reversed relative to the dryland agriculture land cover. The Onkaparinga catchment has a more even split, with slightly more woody native vegetation than dryland agricultural area; however, it had a much higher proportion of orchard and vineyard land cover than either of the two other catchments.

Table 4: Land Cover within the Cudlee Creek Bushfire Area

Land Cover Category	Land Cover within Cudlee Creek Bushfire Area (%)			
	Overall	River Torrens Catchment	Onkaparinga River Catchment	Bremer River Catchment
Woody Native Vegetation	45.3	60.8	45.9	34.3
Non-woody Native Vegetation	2.3	0.2	0.1	5.4
Wetland Vegetation	1.0	1.0	1.5	0.7
Dryland Agriculture	45.3	30.4	41.5	58.2
Exotic Vegetation	0.6	0.6	1.1	0.1
Irrigated Non-Woody Vegetation	1.0	1.0	2.2	0.1
Orchards/Vineyards	2.2	1.0	5.5	0.4
Plantation (Softwood)	1.0	3.2	0.2	0.0
Plantation (Hardwood)	0.6	1.0	0.7	0.3
Urban Area	0.5	0.3	0.9	0.4
Other	0.2	0.1	0.4	0.1

The difference in the proportions of land cover between catchments was relevant in consideration of the effects of bushfire, as metal and PAH concentrations in sediment entering watercourse through runoff may be different based on the vegetation type and anthropological influence on the land (Rai et al. 2019; Zhang et al. 2017). This suggested comparison across the catchment areas may be of value. As part of this, it was also relevant to consider the land use in the area, as native vegetation near agricultural land may also be affected by pesticide and herbicide use. Additionally, the remote sensing of dryland agriculture was not refined enough to distinguish between types of agriculture, which meant that it was unclear what was being farmed in these areas (or if this was part of rural properties). The pathways trace metals enter soils due to agricultural practices for crops or livestock differ (Webber 1981), so clarifying the use of the land was a relevant consideration.

To investigate this, data on the land use in the Cudlee Creek bushfire area was obtained from DPTI (2020), with shapefile data sorted of land use areas sorted into 17 broad classes based on cadastre boundaries. When viewed in the Cudlee Creek bushfire area in Figure 5, it could be seen that the land use in the area was predominantly made up of livestock and rural residential land, with some forestry and reserve areas in the Torrens catchment.

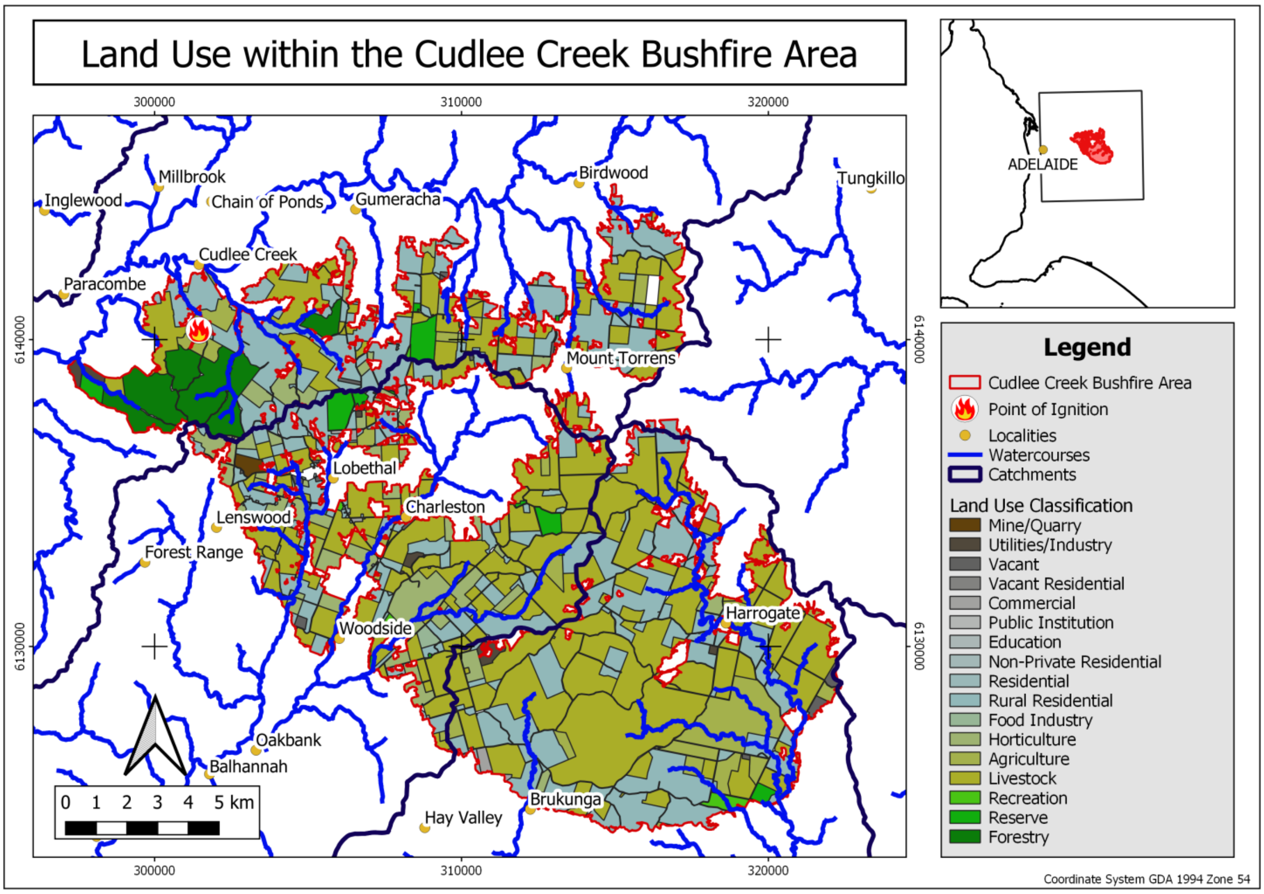


Figure 5: Map of Land Use within the Cudlee Creek Bushfire Area

The calculated proportion of land coverage supported this assessment, with the relative land uses within each bushfire affected area catchment shown in Table 5. These data showed that nearly 60% of the land use in the burnt area was some form of farming (agriculture, horticulture or livestock), with around 30% being rural residential areas. Despite the large percentage of native woody vegetation land coverage, less than 5% of the overall burnt area was in a forestry area, and all of this was located in the River Torrens catchment. This forestry area was the Cudlee Creek Forest Reserve (CCFR), a part of the Mt Crawford Forest Reserve area. This area acts as a native forest catchment to a number of tributaries of the upper reaches of the River Torrens, with the area dominated by species of eucalypts (particularly *Eucalyptus obliqua and Eucalyptus leucoxylon*) (ForestrySA 2016). There remains some area of pine plantation as well (including in the area where the Cudlee Creek bushfire started), which gradually phased out (ForestrySA 2016).

The fact that Figure 4 showed there were still significant tracts of native vegetation land cover in the burnt area indicated that the despite the clearing of land for agricultural and residential land uses, a significant portion of native vegetation remaining on this land. This meant that many of the issues identified in the literature regarding forest catchments would still be relevant, particularly as the land cover in Figure 4 showed native vegetation around the watercourses.

Table 5: Land Use with the Cudlee Creek Bushfire Area

Land Use Category	Land Use within Cudlee Creek Bushfire Area (%)			
	Overall	River Torrens Catchment	Onkaparinga River Catchment	Bremer River Catchment
Agriculture	5.6	3.3	3.4	9.3
Horticulture	6.9	5.6	16.5	1.3
Forestry	4.4	16.1	0.0	0.0
Livestock	44.9	31.0	47.3	56.5
Recreation	0.5	0.1	0.7	0.6
Reserve	1.7	2.6	2.8	0.5
Rural Residential	31.0	40.1	26.2	30.4
Utilities/Industry	0.5	0.8	0.4	0.5
Vacant	0.5	0.4	0.6	0.5
Other	1.3	0.1	2.7	1.0
Not Specified	3.2	3.2	3.7	2.9

The predominance of dryland agricultural land in the region being used for livestock meant that there was less concern regarding the widespread use of pesticides and fertilisers, with livestock contaminant pathways more likely to involve bioaccumulation in effluent from stock feed (Webber 1981). However, areas of horticulture land use, particularly related to the vineyards and orchard land cover, may have elevated levels of chemicals as a result of fertilizers and fungicides (Komárek et al. 2008; Mirzaei et al. 2020). It also indicated that there was the potential for some variation in the way in which metals and PAHs are mobilised due to the different vegetation types. This suggested that comparison of samples collected from the Cudlee Creek forest Torrens watershed and the Onkaparinga River and/or Bremer River catchments could provide insight into potential differences in bushfire effects.

1.4.7. Native Vegetation in the Cudlee Creek Area

Biological surveys of the Southern Mount Lofty Ranges (SMLR) conducted by Armstrong, Croft and Foulkes (2003) provided approximate compositions of the native vegetation in the region affected by the Cudlee Creek bushfire. *Eucalyptus obliqua* was present in most floristic groups observed in quadrats near Cudlee Creek, Charleston and Lobethal, and was observed as being one of the two dominant species in the entirety of the SMLR (Armstrong, Croft & Foulkes 2003), including within the CCFR (ForestrySA 2016). Study on *Eucalyptus obliqua* has indicated that it is capable of significant uptake of metals, particularly iron and manganese (Barry et al. 2015). Studies on other eucalypt species have also demonstrated higher uptake and retention of metal concentrations (Campos et al. 2015; Mok et al. 2013), which may have an effect on metal mobilisation when these trees are burnt.

1.4.8. Cudlee Creek Bushfire Summary

The Cudlee Creek bushfire presented the opportunity to apply the knowledge gained from the literature review to undertake a practical case study monitoring contamination in water due to bushfire. Geospatial investigation of the area burnt in the Cudlee Creek bushfire identified the major watercourse and waterbodies that were at potential risk of contamination from both ash and soil mobilisation. Additionally, analysis of the differing land cover and land uses between catchment areas affected by the bushfire indicated that there was an opportunity for comparison of vegetation cover and its effect on metals and PAH mobilisation and therefore waterbody concentrations. Ultimately, this research will provide a baseline for assessment of ongoing risk to waterbodies caused by bushfires now and into the future.

1.5. Research Aims and Objectives

Based upon the literature review, it appeared that minimal research had been conducted in the Australian context on the mobilisation of metals and PAHs into watercourses and waterbodies due to bushfire. With evidence that Australia's eucalypts may act as a significant sink for metals that could be remobilised in bushfire events, and the increasing awareness of bushfire generated PAHs as water contaminants, examination of the impact of these contaminants is necessary. The Cudlee Creek bushfire of December 2019 therefore presented an opportunity to investigate whether the release of contaminants via bushfire was an issue of concern in the South Australian context.

It was hypothesised that based on the evidence from the literature review indicated that there was likely to be an increase in the concentration of metals and PAHs as a result of the Cudlee Creek bushfires. However, it was unclear as to whether such an increase would be sufficiently high to approach the ADWG limits. Additionally, the difficulty of detecting low levels of PAHs meant that alternative means of reaching conclusions about their effects may be necessary. The timing of the increase was also expected to be varied dependant on the rainfall-runoff experienced in the catchment. As such, this research had two main aims:

i. To determine whether concentrations of metals and PAHs in waterbodies were affected by bushfire events.
ii. To understand whether the Cudlee Creek bushfire in 2019 affected water safety in the region, potable or otherwise.

In service of these aims, the following objectives were identified as being critical:

i. To determine locations in the Cudlee Creek bushfire region where contaminants released by bushfire may enter into watercourses or be affected by upstream contamination.
ii. To investigate surface water at these locations over multiple rounds of sampling to test for metals and PAH concentrations.
iii. To maintain a photo set monitoring the vegetative recovery at these sampling locations for each round of sampling to supplement the laboratory testing.

2. MATERIALS AND METHODS

2.1. Methodological Approach

As outlined previously, the rationale of this research was to investigate if water contamination from bushfires in South Australia posed a risk to human health. From the literature review, trace metals and PAHs were identified as contaminants of particular concern that were generated and mobilised by bushfires. The collection of data within the literature in this regard was overwhelmingly quantitative, with data obtained primarily through collecting physical samples of sediments and/or water. There was some variation in methodologies, as while most studies of contaminants relied on the assessment in the wake of bushfire events (e.g. Gabos et al. (2001); Kim, Choi and Chang (2011); Mansilha et al. (2019)), others conducted controlled experiments to replicate these conditions to gain understanding of contaminant behaviour (e.g. Freeman and Cattell (1990); Ross et al. (2018)). Some studies supplemented this with surveys of affected individuals to obtain estimates of bushfire characteristics; however the overall influence of these data were small and still framed in a quantitative context (Spinks et al. 2006). Qualitative data however was used for the monitoring of the recovery of bushfire affected watercourses (EPA SA 2008), which presented a useful method to acquire parallel data that could be used to support quantitative data collection.

Based on the methodologies of similar studies, the data collection for this thesis focussed the collection of water samples from bushfire affected watercourses for quantitative analysis. Collection of water samples for testing of metals and PAHs was considered the best indication of the security and level of risk to the watercourse. Additionally, due to limitations of interaction with members of the public during the data collection phase, the collection of qualitative data from members of the public regarding experienced water quality in the region (taste, appearance etc.) was not feasible.

The literature review also indicated that longitudinal study was best for the purpose of assessing the ongoing risk to the catchment beyond just the immediate aftermath of bushfires (Kim, Choi & Chang 2011; Mansilha et al. 2019; Olivella et al. 2006). This longitudinal nature of study meant that a photo set was able to be built monitoring change in the local ecosystem that surrounded the water body sampled. This use of qualitative data was supported by similar monitoring conducted by the EPA SA (2008) on the recovery from bushfire along the Tod River on South Australia’s Eyre Peninsula.

2.2. Ethical Considerations

The data collection and reporting components of this project were expected to have minimal ethical considerations, due to the largely quantitative nature of the data necessary to collect. No in-person interviews or personal information was expected to be used to form any part of the conclusions. Where appropriate, it was anticipated that it may be necessary to obtain access to private land in order to conduct sampling, and consent forms were provided to inform and obtain permission from landowners.

The context of the COVID-19 pandemic did, however, alter the design of this research as a result of ethical considerations. Initially, this research was anticipated to be conducted on residential dams in the Cudlee Creek area, where direct pathways of human exposure to water supply could be longitudinally studied. However, as this design of this research began in February 2020, the initial wave of the COVID-19 pandemic required an alteration of this design. The in-person interaction with members of the public that would have been required was prohibitive. Additionally, this presented a risk to the longitudinal nature of the study, due to the uncertainty at the time regarding freedom of movement. As a result, the study was designed to ensure that any sampling locations were publicly accessible or that entry on to the site could be arranged remotely.

It was important that the water being sampled did not have a direct pathway for human ingestion in the same manner as water in residential dams. Water from Cudlee Creek eventually enters into the Kangaroo Creek Reservoir, while the water in the Onkaparinga Catchment will enter the Mt Bold Reservoir. Given the size of these reservoirs however, the dilution effect of this was uncertain but likely very significant. Hence the contaminants entering into the watercourses should be considered as a proxy for dam assessment, while acknowledging that there may be differences in accumulative potential.

2.3. Research Design

The design of the approach was to meet the two aims outlined for the research: to identify whether concentrations of PAHs and metals were affected by bushfire, and whether any change poses a threat to human health. The conclusion from the literature regarding methodological practices in similar studies was that quantitative measurement of contaminant concentrations in water bodies was the most effective method of achieving these results, but that this could be supported by some qualitative observation data. Evidence from the literature review indicated that water from forest catchments was at risk due to ash and topsoil movement, and that there were also potential risks to drinking water in water tanks as a result of ash movement. A gap within this knowledge was that areas prone to bushfire are likely to have dams, which are subject to both overland flow and ash deposition. Like water tanks, dams act as a concentration point for contaminants to potentially accumulate, but unlike water tanks, are subject to soil mobilisation via overland flow as well as ash disposition in the aftermath of bushfires. Dams also pose a potential pathway for influencing human health, as while they are less likely to be used for drinking water, use for agriculture of crops and livestock could potential issues.

However, as the impact of the COVID-19 pandemic made this avenue of research untenable, it was decided that an alternative method of sampling the watercourses around the area affected by the Cudlee Creek bushfire was appropriate. Evidence from the literature review demonstrated that sampling watercourses was an effective method of assessing metals and PAH contamination and can be supplemented with indicators of health such as the use of visual logs. Watercourses draw from a greater catchment area than individual residential dams, so may offer a more diverse insight into contaminants released by bushfires. Additionally, Cudlee Creek and the Onkaparinga watershed discharge into reservoir dams (Kangaroo Creek and Mt Bold respectively) which are used in Adelaide’s water supply, so indication of significant contaminant flow would present potential water quality issues on a wider scale.

This research needed to account for variation in the way in which these contaminants entered the environment. Evidence suggested that data collected in the first few months is the most critical in determining health risk, as this is when concentrations are highest. To account for this variation, a longitudinal study was conducted. Additionally, the incorporation of qualitative data by collecting a photo set of the sampling location acted as a method that could potentially provide an indication of deleterious environmental effects that were missed in between sampling rounds.

Based on the methodological review and discussion of sampling targets, the core elements of the methods for research are outlined in Table 6. Further information necessary to fulfil each element is presented within this methods section.

Table 6: Outline of Study Method Intent

Monitoring Plan Component	Statement of intent	Required Information
Target Area	This research will be conducted on surface watercourses in the area of the Cudlee Creek bushfire	-
Target Contaminants	This research will use testing to identify concentrations of metals and PAHs, with a focus on the trace metals identified in Table 1 and the PAHs listed in Table 2	Identification of sample site (2.4 Sample Site Identification)
Sampling Duration	This research will collect samples across the target area in the first sampling event, which will then be used to decisions on targeted sampling based on cost/benefit	Initial sampling event
Sample Method	This research will collect surface water samples from locations within the specified area based on sampling duration. This research will collect photos to monitor stream health at all sampling locations.	Specification of data collection process (2.5 Data Collection Method)
Sample Analysis	This research will have these samples analysed and use these data to determine if there is evidence of the effect of bushfire	Outline of sample analysis procedure (0 Sample Analysis Procedure)
Sampling Frequency	This research will continue to collect data from these sampling locations over multiple rounds	Determination of frequency of sampling (0. Data Collection Frequency)

2.4. Sample Site Identification

2.4.1. Sample Site Criteria

The use of a quantitative data methodology for this research meant that the identification of appropriate sample sites was of critical importance. Samples collected without careful consideration could lead to misleading or mistaken conclusions about the effects and dangers of bushfires on watercourses. As such, it was necessary to develop criteria that would effectively identify locations that would be both representative of the conditions of post-bushfire watercourses, while also representing the magnitude of risk that these watercourses face.

Based on the literature review, there was growing concern about the increased intensity of fire events occurring due to climate change, which at the local scale translated to an increase in the severity of burning (van Oldenborgh et al. 2021). Although the literature was mixed regarding whether greater burn severity leads to greater PAH generation (Campos et al. 2019; Chen et al. 2018; Kim, Choi & Chang 2011), the effect of severe burning on increased mobilisation of soils was well established (Shakesby & Doerr 2006; Smith et al. 2011b). Ensuring that sampling was conducted near areas of severe burning meant that areas that posed the highest risk of mobilisation were captured.

Another conclusion from the literature review was the fact that water sampling in post-bushfire environments was relatively scarce, particularly regarding testing for PAHs in water. With the focus of this research on the potential water contamination pathways of bushfire that could affect human health, sample collection was predicated on the presence of water in bushfire areas. The investigation into the land cover of Cudlee Creek meant land use was also identified in the investigation of Cudlee Creek as being worthy of consideration when selecting sampling locations (see Section 1.4.6).

Due to the ethical considerations of this research, it was apparent that any sample locations could not be sought from private land. This meant that samples had to be obtained from areas considered public; additionally, these locations had to safe and easy to access. Based on this information, criteria for locating the sample sites shown in Table 7 were developed.

Table 7: Site Selection Criteria

No.	Criteria	Details
1	Burn Severity	Sample sites should as near to areas of the most severe burning as possible
2a	Sample site proximity to Bushfire	Sampled watercourse sites must be in an area immediately affected or downstream from an area of the watercourse affected by fire.
2b	Control site proximity to Bushfire	Control watercourse sites should have similar characteristics to sample sites, and not downstream of burnt areas
3	Streamflow	Sampled watercourses sites must be likely to contain water throughout the duration of the research
4	Catchment Comparison	Sample sites should span at least two of the Cudlee Creek bushfire affected catchments
5	Site Accessibility	Sites must be accessible (avoiding private land) and safe to enter

Based on these criteria, information about the area burnt by the bushfire, the watercourses and watersheds in the Cudlee Creek region, and the roads in the area was required. Given the large area that the fire affected, it was desirable to get a wide spatial distribution of sampling sites. To identify sites that fitted these criteria, investigation of the area using GIS was used (described below). Prior to the first round of sampling, the various sites were visited and adjustments to site locations were made due to inaccessibility or the discovery of new relevant sites. The results of the GIS investigation were then adjusted based on GPS location at the time of sampling.

2.4.2. GIS Interpretation of Sample Site Criteria

2.4.2.1. Criterion 1: Burn Severity

The severity of vegetation burning was a critical part of the selection criteria for sample points within the Cudlee Creek bushfire area. Estimation of the burn severity in this area required further GIS investigation, with multispectral instrumentation (MSI) satellite imagery used to calculate the Normalised Burn Ratio (NBR). The NBR normalises the reflectance range of MSI imagery so pre-fire and post-fire imagery can be compared to calculate the Normalised Burn Ratio (ΔNBR), with this processed imagery used to index the burn severity. The calculation of these values and creation of the ΔNBR imagery is further detailed in Section 2.4.3.

MSI satellite imaging is obtained from the Copernicus Sentinel-2 satellite, run by the European Space Agency (ESA). The imagery datasets used in this analysis are listed in Table 8, with imagery from the days preceding and following the outbreak of the Cudlee Creek fire on 20

December 2019 was obtained to data most representative of the impact of the bushfire. The use of 'Last Fire' dataset from DEW (2020b) provided a useful sense check on the ∆NBR raster calculated.

2.4.2.2. Criterion 2: Bushfire Proximity to Watercourses

The second criterion states that sample sites were within or downstream of the bushfire area and that control sites were not, which was relatively straightforward for analysis. Tributaries of the catchment that were not downstream of fire affected regions were unlikely to have experienced any contamination from metal mobilisation due to rainfall-runoff as area of the catchment was not affected by fire. However, this did not eliminate the potential that PAH mobilisation via wind erosion of ash could have spread to these areas, so PAH results were assessed with the knowledge that this may affect results.

This criterion required the GIS dataset of watercourses from DEW (2016b) which was then be compared against the ∆NBR imagery to determine watercourse locations affected by severe burn for sampling locations and unaffected areas for control locations. The distance between these areas and the watercourses was assessed to identify regions where the proximity of the severely burnt areas was close to the watercourse.

2.4.2.3. Criterion 3: Streamflow

For the selected sample sites to provide useful data on contaminants in water, it was considered advantageous for the watercourse not to be dry. This was particularly relevant given the longitudinal nature of the research, where repeated sampling was used for temporal comparison contaminant load. Use of the watercourses dataset from DEW (2016b) was used to locate where sampling could take place, however in order to avoid selecting ephemeral watercourses, the Strahler stream order was used as a proxy indication of consistent flow. Strahler stream order assigns the outer tributaries of the catchment an order of one, which is increased as the tributary joins another of the same order; if a lower order stream joins a higher order stream, the higher order number remains but does not increase(Strahler 1957). Field study of stream order indicated that this definition can change significantly based on seasonal variations in rainfall, with changes of up to two orders observed (Godsey & Kirchner 2014). As data from DEW (2016b) on watercourses in South Australia has been collected since 1990, it likely had captured ephemeral streams within the dataset. Thus it was considered an appropriate as proxy measure of streamflow to adjust this shapefile to only consider watercourses of stream order 3 or above for sampling locations.

2.4.2.4. Criterion 4: Catchment Comparison

Land cover assessment of the Cudlee Creek burnt area noted that the Torrens Creek catchment had significantly more native vegetation than the Onkaparinga or Bremer River catchments. To provide some comparison of the influence of bushfires on forest watersheds and agricultural areas, sampling sites sampling sites were located in multiple catchments. Due to the large spatial spread of the burnt area, for the sake of practicality, it was decided that only two of the catchments would be examined. As the River Torrens catchment was the most relevant to this research as a forest catchment, sample sites in this area were required. The large spatial scale of the bushfire affected area meant that for practicality reasons sampling in the closer Onkaparinga catchment was desirable. Selection of sampling sites was thus targeted in these catchments, with 10 bushfire affected sites selected to examine the effects on different tributaries, 5 in each catchment. An additional 5 locations were selected as control samples for comparison in areas that were unaffected by bushfire directly or upstream. A total of 15 sampling sites were selected as it provided a sufficiently large sample size in a variety of bushfire-affected areas, within the budgetary constraints and the practicalities of travel, access and collection during sampling events. The database of catchments from DEW (2016a) was used to ensure that sampling was conducted in these two areas evenly.

2.4.2.5. Criterion 5: Site Accessibility

The accessibility of locations to complete sampling was a relevant consideration from a safety and monitoring efficiency perspective. The DPTI (2016) dataset of roads was considered appropriate measure to provide context as the remoteness of areas of the watercourse. Road class was filtered to avoid rural tracks and off-road areas as much as possible.

2.4.2.6. Data Summary

The dataset required for the selection of sample sites based upon the proposed criteria are listed in Table 8.

Table 8: Spatial Datasets Used for Cudlee Creek Bushfire Sample Site Selection

Feature	Data Name	Reference	Data Accessed
Catchments	WATER_Catchments_GDA94	DEW (2016a)	16/03/2020
Last Fire	FIREMGT_LastFire_GDA94	DEW (2020b)	25/03/2020
Localities	Gazetter2012_SA_EAST	(Geoscience Australia 2013)	22/05/2021
Roads	Roads_GDA94	DPTI (2016)	25/03/2020
Satellite MSI Imagery	S2B_MSIL2A_20191208T003659_N0213_R059_T54HUG_20191208T022230	Copernicus Sentinel-2 data (2019a)	25/03/2020

Satellite MSI Imagery	S2B_MSIL2A_20191218T003659_N0213_R059_T54HTG_20191218T022136	Copernicus Sentinel-2 data (2019b)	07/05/2021
Satellite MSI Imagery	S2B_MSIL2A_20191218T003659_N0213_R059_T54HUG_20191218T022136	Copernicus Sentinel-2 data (2019c)	07/05/2021
Satellite MSI Imagery	S2B_MSIL2A_20191228T003659_N0213_R059_T54HTG_20191228T022034	Copernicus Sentinel-2 data (2019d)	25/03/2020
Satellite MSI Imagery	S2B_MSIL2A_20191228T003659_N0213_R059_T54HUG_20191228T022034	Copernicus Sentinel-2 data (2019e)	25/03/2020
Satellite MSI Imagery	S2A_MSIL2A_20200112T003701_N0213_R059_T54HTG_20200112T030410	Copernicus Sentinel-2 data (2020a)	07/05/2021
Satellite MSI Imagery	S2A_MSIL2A_20200112T003701_N0213_R059_T54HUG_20200112T030410	Copernicus Sentinel-2 data (2020b)	07/05/2021
Topography	GEODATA TOPO 250K Series 3	Geoscience Australia (2006)	27/04/2020
Watercourses	Watercourses	DEW (2016b)	16/03/2020

2.4.3. Cudlee Creek Bushfire Burn Severity

2.4.3.1. Burn Severity Calculation Method

The use of GIS software to map and classify burn severity is widespread, usually in the form of multispectral data comparisons between vegetation reflectivity before and after fires (Fassnacht et al. 2021; Filipponi 2018; Pepe & Parente 2018). Burn severity refers to the ecological changes caused by fire, including “the physical and chemical changes to the soil, conversion of vegetation and fuels to inorganic carbon, and structural or compositional transformations that bring about new microclimates and species assemblages” (Key & Benson 2006). Definitive measurement of burn severity has remained elusive (Cocke, Fulé & Crouse 2005; Key & Benson 2006), however many methods have proposed ways of calculating indices that allow for analysis of fire affected area.

A number of methods were considered for assessing burn severity the Cudlee Creek bushfire; most popular in the literature was the use of the normalised difference vegetation index (NDVI) or the Normalised Burn Ratio (NBR) (Cocke, Fulé & Crouse 2005; Fassnacht et al. 2021; Joehnk et al. 2020; Key & Benson 2006; Massetti et al. 2019; Pepe & Parente 2018). Some more complex methods were also considered including the Burned Area Index for Sentinel-2 (BAIS2) (Filipponi 2018) and the linear regression vegetation structure perpendicular index (VSPI) model (Massetti et al. 2019). Common among these methods was the use of satellite MSI that captured imagery that separated the received light into specific wavelengths. The different spectral bands available from Sentinel-2 MSI satellite are shown in Figure 6, with various resolutions of data available in the visible range (~400-700 μm), near infrared (NIR) range (~700-1200 μm) and shortwave infrared (SWIR) range (~1200-2500 μm).

Adapted from ESA's Sentinel-2 team (2015), p.8.

Figure has been removed due to Copyright restrictions.

Figure 6: Spectral Bands by Wavelength (ESA's Sentinel-2 team 2015)

This spectral imagery was used due to the fact that healthy and burnt vegetation have significantly different reflectance relationships with different spectral wavelengths. An approximation of this relationship is shown in Figure 7, which demonstrated that vegetation in the near infrared NIR band was significantly more reflective than burnt vegetation; this relationship was inverted in the SWIR wavelengths.

Adapted from Pepe & Parente (2018), p.229, Figure 2.

Figure has been removed due to Copyright restrictions.

Figure 7: Spectral Curves of Healthy and Burnt Vegetation (Pepe & Parente 2018)

For the purposes of this research, it was determined that the widely used and relatively simple NBR calculation was sufficient to gain an understanding of where the most intense region of burning was, which then identified the locations appropriate for sampling. As this measurement of burn severity was only required for scouting sampling location, the more complex BAIS2 calculation was deemed too process intensive, as it required processing of 5 separate spectral bands for the calculation of each image (Filipponi 2018), with only minimal improvement in sensitivity. The VSPI required more complicated linear regression modelling, and was only significantly more sensitive in comparison to the NDVI and NBR over longer term analyses of recovery of bushfire areas (Massetti et al. 2019). Finally, the NDVI was similar in complexity and processing requirements to the NBR, but had been shown to be an inferior approximation of burn severity to the NBR (Key & Benson 2006; Pepe & Parente 2018).

2.4.3.2. NBR Calculation

As demonstrated in Figure 7, the reflectance of healthy and burnt vegetation have very different relationships over the spectrum. This relationship is exploited by the NBR at the wavelengths where the difference between the reflectance is theoretically at its greatest. This was expressed as a ratio calculated using the formula in Equation 1.

$$NBR = \frac{NIR - SWIR}{NIR + SWIR} \qquad 1)$$

The NBR is calculated based on rasters of the burnt area at NIR and SWIR wavelengths obtained from multispectral satellite imagery. NBR rasters are calculated for imagery before and after the fire, which can then be used to calculate the delta NBR (∆NBR). The calculation for the ∆NBR is shown in Equation 2.

$$\Delta NBR = NBR_{prefire} - NBR_{postfire} \tag{2}$$

This value of ∆NBR can then be used to evaluate the severity of the bushfire, as well as areas of high regrowth when imagery is compared over longer periods. ∆NBR is assessed on the burn severity index in Table 9, which provides an indication of the relative damage caused to the land cover in each pixel.

Table 9: Burn Severity Index (adapted from Key and Benson (2006))

∆NBR	Burn Severity
<-0.25	High post-fire regrowth
-0.25 to -0.1	Low post-fire regrowth
-0.1 to 0.1	Unburnt
0.1 to 0.27	Low Severity
0.27 to 0.44	Low-Moderate severity
0.44 to 0.66	Moderate- High Severity
>0.66	High Severity

To estimate the severity of bushfire, these values should be obtained from as closely before and after the fire as possible (White et al. 1996), as land cover can change relatively quickly as vegetation recovers. ∆NBR calculated over significant time periods can be subject to factors such as seasonal variations in growth, which may not be representative of the impact of fire (Massetti et al. 2019).

2.4.3.3. Cudlee Creek NBR

To calculate the NBR, multispectral satellite imagery of the Cudlee Creek area from before and after the fire was required. As satellite data used in the calculation of the NBR required spectral imagery in the NIR and SWIR bands, data from the Sentinel-2 satellites from the European Space Agency Copernicus program was used, as it was freely available and possessed the MSI imaging required.

Sentinel-2 imagery is obtained from two similar satellites with MSI imaging sensors. These satellites orbit in an approximately 10 day period, with each being offset to providing satellite imagery of the world’s locations every 5 days. The MSI imagery available from these satellites is divided into 13 bands, with the wavelength range and resolutions outlined in Table 10.

Table 10: Sentinel 2 Bands (adapted from ESA (2015) & Pepe and Parente (2018))

Band No.	Light Band	Feature	Central wavelength (nm)	Bandwidth (nm)	Resolution (m)
1	Visible	Aerosol	443	20	60
2	Visible	Blue	490	65	10
3	Visible	Green	560	35	10
4	Visible	Red	665	30	10
5	NIR	Vegetation Red Edge-1	705	15	20
6	NIR	Vegetation Red Edge-2	740	15	20
7	NIR	Vegetation Red Edge-3	783	20	20
8	NIR		842	115	10
8A	NIR	Narrow (Water Vapour Adjusted)	865	20	20
9	NIR	Water Vapour	945	20	60
10	SWIR	Cirrus Detection	1375	30	60
11	SWIR		1610	90	20
12	SWIR		2190	180	20

The calculation of the NBR in Equation 1 required data from NIR and SWIR bands, which corresponded to band 8 and band 12 (Filipponi 2018; Pepe & Parente 2018). The use of the narrow NIR band 8A is also common in the literature (Fassnacht et al. 2021; UN-SPIDER n.d.). The 8A band had the benefit of data adjusted to avoid water vapour distortion and is presented in a similar resolution as SWIR band 12, which eliminated issues of scaling between resolutions (Pepe & Parente 2018). There was little concern over lower resolution at 20 m; the NBR was calculated to be indicative instead of for experimental purpose, which meant this level of resolution was considered sufficient.

For the NBR to be calculated, imagery of sufficient quality was required for the area, which required there to be an absence of cloud obstructing the study area. Additionally, the size and location of the Cudlee Creek bushfire overlapped between MSI imaging granules, which meant that the multiple granules were required. Imagery from a range of dates around the ignition of the Cudlee Creek bushfire on 20 December 2019 was obtained from the Sentinel-2 Sci-hub (Copernicus 2021). Unobstructed imagery was obtained from 8 December 2019, 18 December 2019, 28 December 2019 and 12 January 2020, so that the best representation of the burnt area was found. Other dates around these either were obstructed by cloud or had data unavailable.

Rasters from the different image granules for corresponding data were imported into QGIS and merged, with NBR calculation using Equation 1 performed on the combined imagery. ∆NBR calculation was performed on the rasters using various combinations of the pre-fire and post-fire imagery. Experimentation with these data showed that the best representation of the burn scar occurred when using the pre-fire NBR Cudlee Creek fire started on 20 December 2019, it was determined that the pre-bushfire imagery used would be from 18 December 2019. The post-bushfire imagery captured on 28 December 2019 was chosen as it gave a better indication of the maximum severity of the burn area, in line with the observation of White et al. (1996). Although at this point the fire was still technically uncontrolled, the additional burning between this date and the 12 January was minimal. In fact by 12 January 2020, burn severity had already reduced in some area, despite the fact the fire was not declared safe until 22 January (Government of South Australia 2020). This was likely due to the greatest intensity of the Cudlee Creek fire being on the first day, meaning that imagery from 28 December 2019 was close to the date at which most sever burning took place in a majority of the burnt area.

The ∆NBR for the Cudlee Creek bushfire between 18 December and 28 December 2019 was calculated and is shown in Figure 8. The burn severity index based on the values in Table 9 was used to show the most severe burning occurred in the north west of the catchment in the area around the point of ignition. This area was largely in and around the CCFR, where there was a significant eucalypt plantation (ForestrySA 2016). Evidence from the land cover analysis in Figure 4 suggested that this area had significant native woody vegetation, as well as other areas in the north of the burnt area which also exhibited evidence of high severity burning. Further to the south-east in the agriculture dominated areas of the Onkaparinga and Bremer River catchments, were low-moderate or moderate-high severity burning. This analysis indicated that sampling in the River Torrens catchment, particularly around the CCFR, was important for understanding the levels of contaminants that could be generated by bushfire in a forest catchment.

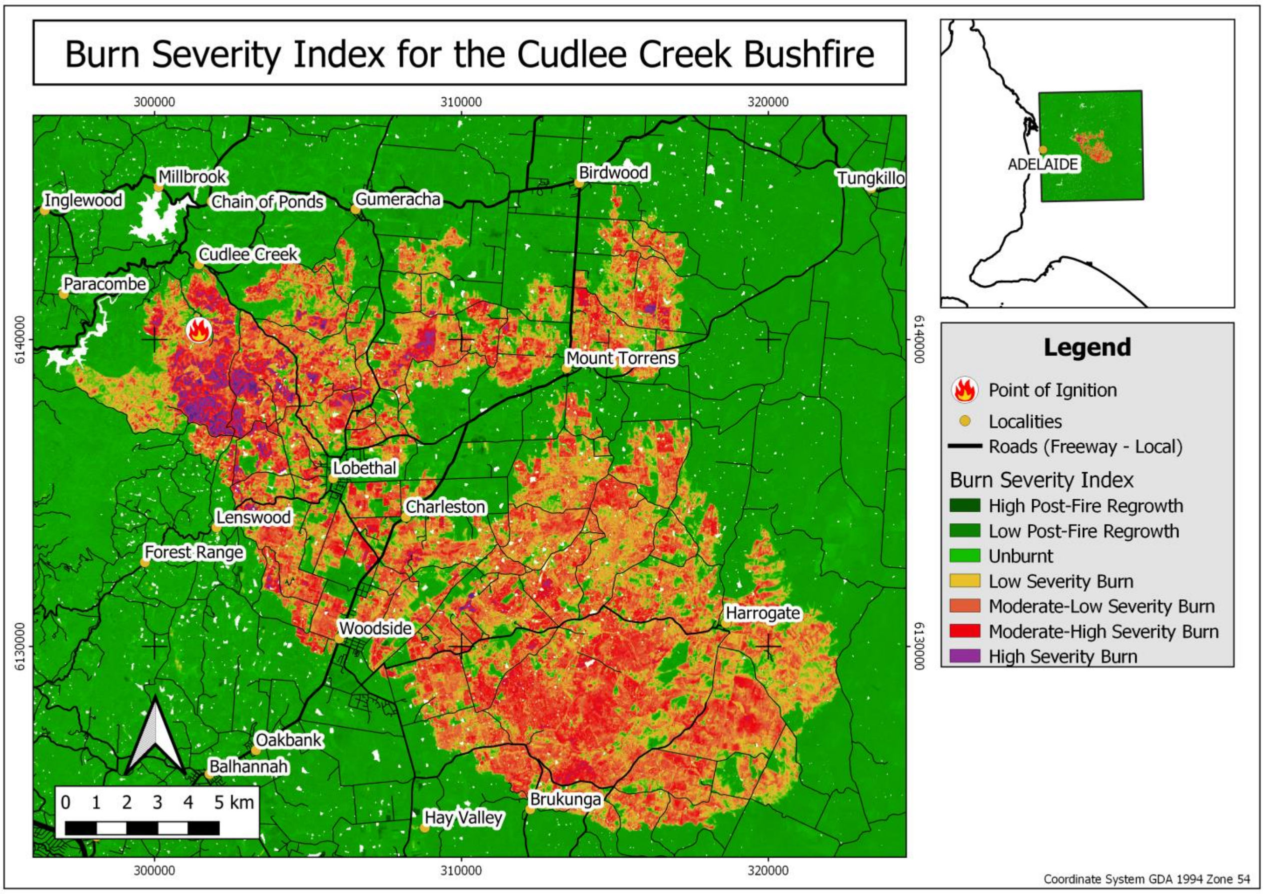


Figure 8: Map of the Burn Severity Index for the Cudlee Creek Bushfire

2.4.3.4. NBR Limitations

It should be noted that slope can negatively affect the performance of the NBR, as in steep areas shadowing can create false impression of lack of vegetation reflectivity (Fassnacht et al. 2021; Hoy et al. 2008). The areas that appeared the most severely burnt in Figure 8 also were located in the steeper regions of the bushfire area (Figure 2). When the area was ground truthed, it was apparent that this analysis was accurate, as there had received significant damage to the eucalypt populations on the slopes in these areas Figure 9.

Figure 9: Vegetation Damage in the CCFR

2.4.4. Sample Sites

The calculated burn severity map in Figure 8 was used with the other GIS data from Table 8 to provide an estimate for locations that would be suitable for sampling. The locations were then visited in preparation for the first sampling event, with adjustments made for locations deemed unsuitable.

The burn severity map in Figure 8 demonstrated that the north-west of the burn area was the most severely affected, and that this was an indication that sampling should take place as near as practicable to it. This was affected by the fact that entry into the CCFR, which corresponded with the area of highest burn severity, was limited due to health and safety concerns. Sites S02 and S04 were located at the fence line of the CCFR and so were able to be sampled, but waterbodies further into the area were not. The eventually reopening of this area allowed for an investigation into the area during CCWS06, but waterbodies further into the reserve were predominantly dry. Only one addition was made to the sampling map.

Sites were numbered starting from north to south, and adjustments were made to their location bas on assessment of their suitability on the ground. 15 sites were originally planned, with 5 bushfire and 3 control sampling locations in the River Torrens catchment, and another 5 bushfire and 2 controls sampling locations in the Onkaparinga River catchment. The combination of GIS data and on-the-ground observation produced the sampling locations in Figure 10.

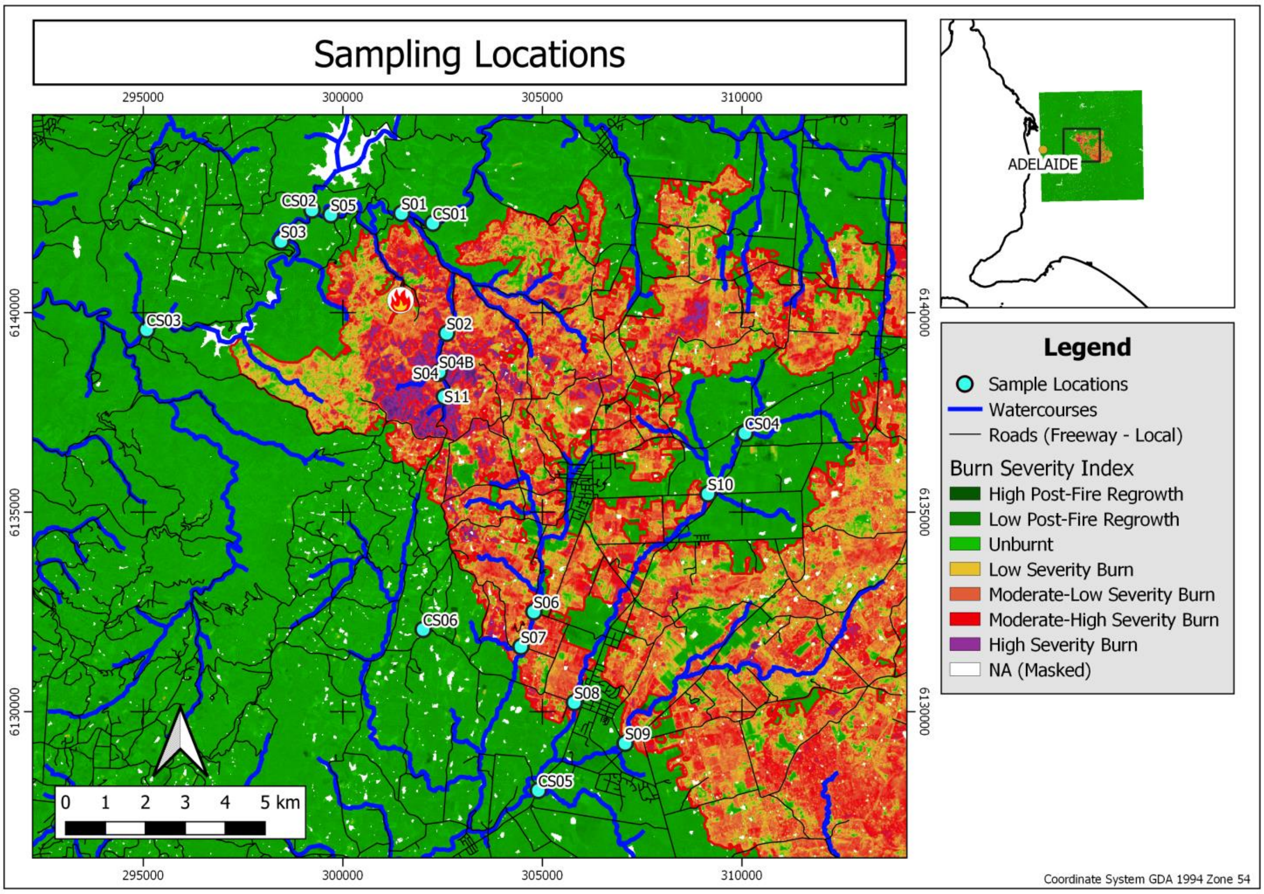


Figure 10: Map of Sampling Location

In addition to the predicted 15 locations for sampling, observation on the ground identified three additional sites suitable for sampling.

- CS06 – a dammed area that appeared accessible at the beginning of sampling event. Became inaccessible due to crop growth by the 4th sampling event.
- S04B – named due to proximity to S04, but related to a distinct tributary joining with S04.
- S11 – an additional site in the CCFR discovered in the last sampling event, and sampled due to proximity to high severity burn location

Overall 18 sites were sampled in some combination. The name and location of each site is listed in Table 11, as well as the indication of which catchment the sample site was in.

Table 11: Summary of Sample Sites

Sample Site	Sampling Location	Watercourse	Catchment
S01	34°50'25.7"S 138°49'44.5"E	River Torrens	River Torrens
S02	34°52'04.6"S 138°50'24.5"E	Fox Creek	River Torrens
S03	34°50'46.6"S 138°47'43.9"E	River Torrens	River Torrens
S04	34°52'37.0"S 138°50'17.6"E	Fox Creek	River Torrens
S04B	34°52'35.5"S 138°50'17.2"E	Fox Creek	River Torrens
S05	34°50'26.4"S 138°48'33.8"E	River Torrens	River Torrens
S06	34°55'52.1"S 138°51'45.8"E	Western Branch of the Onkaparinga River	Onkaparinga River
S07	34°56'20.5"S 138°51'32.1"E	Western Branch of the Onkaparinga River	Onkaparinga River
S08	34°57'06.6"S 138°52'24.1"E	Onkaparinga River	Onkaparinga River
S09	34°57'40.8"S 138°53'13.0"E	Inverbrackie Creek	Onkaparinga River
S10	34°54'19.1"S 138°54'48.4"E	Onkaparinga River	Onkaparinga River
S11	34°52'55.9"S 138°50'21.8"E	Fox Creek	River Torrens
CS01	34°50'35.7"S 138°50'14.3"E	River Torrens	River Torrens
CS02	34°50'25.7"S 138°48'16.4"E	River Torrens	River Torrens
CS03	34°51'56.2"S 138°45'29.7"E	River Torrens	River Torrens
CS04	34°53'30.5"S 138°55'17.8"E	Onkaparinga River	Onkaparinga River
CS05	34°58'17.6"S 138°51'46.4"E	Mitchell Creek	Onkaparinga River
CS06	34°56'06.3"S 138°49'55.5"E	-	Onkaparinga River

2.5. Data Collection Process

2.5.1. Data Collection Basis

The sampling procedure used in this research was designed based on the surface water guidelines described by the Environmental Protection Authority South Australia (Duncan et al. 2007). These guidelines were developed with particular reference to on two pieces of South Australian legislation: *Environmental Protection Act 1993* and the *Environment Protection (Water Quality Policy 2003).* The formulation of these guidelines was based upon the AS/NZS 5667.6: 1998 standard (itself based on the ISO5667:6 standard used by Sequeira et al. (2020) and Mansilha et al. (2019)), which indicated that this was an appropriate and relevant method design.

2.5.2. Data Collection Equipment

The targets of sampling in this research were metals and PAHs, so other water quality parameters were not considered relevant and not tested for. Additionally, samples were tested for total metals, so no field filtering was required. Sampling equipment necessary to conduct in-field sampling included:

- Sample bottles
    - Plastic bottles for metals sampling (at least 1x no. of samples to be collected, plus additional for replicate sampling)
    - Brown glass bottles for PAH sampling (at least 2x no. of samples to be collected)
- Water collection bottle
- Extendable water sampling rod
- Esky (with ice)
- Deionised water

The creation of a photo set as an additional data point was a critical part of this project, and so a camera was necessary for completing the sample process. A template was set up in Ersi Survey123 to provide accurate location data and notes of observations about the site.

2.5.3. Data Collection Procedure

Based on the details in Duncan et al. (2007) procedure for the collection of water samples was outlined in Table 12.

Table 12: Water Collection Procedure

No.	Step	Explanation
1	Choose sample Location	Chose location at watercourse bank from which to sample - approx. nearest point fire-affected vegetation if present
2	Record Field Observations	Note any observations or changes in catchments - Enter site details in ArcGIS Survey123 App - Photograph sampling location, 3 perspectives - Record any observations about site characteristics/differences
3	Selected Required Bottles	Select the sample bottles required for surface water sampling. Bottles provided by Envirolab, labelled for specific testing use. - Metals sampling: 1 plastic bottle (some pre-acidified depending on bottles provided by Envirolab) (approx.100 mL) - PAH sampling: 2 brown glass bottles (no acidification) (approx. 300 mL total) - Water collection bottle to decant into sampling bottles
4	Label bottles	Enter the required information on each bottle. - Sampling Event Name (CCWSXX) - Sample Name (SXX for bushfire sites, CSXX for control sites) - Date Collected - Collector by (initials)
5	Decontaminate	Decontaminate the water collection bottle with demineralised water
6	Collect water sample	If safe, move to edge of watercourse and use sample collection rod to reach location approximately 1.5 m away from shore.
7	Fill water collection bottle	Fill collection bottle by entering it into water body approximately 30 cm deep. Ensure that water collection bottle does not stir up sediments at base of watercourse.
8	Rinse water collection bottle	Empty water collection bottle downstream of where it was filled. - Repeat 3 times.
9	Decant water collection bottle	Fill collection bottle and return it to shore
10	Discard remaining water	Decant the collection bottle into sampling bottles - Decant glass bottles first, then metals - Total metals collected, no field filtering

11	Dispose of excess water	Empty remaining water into watercourse - Water collected from surface water at that location, so may be disposed of onsite
12	Refrigerate samples	Place samples in esky, to be kept at 4°C in accordance with Duncan et al. (2007) for transfer to laboratory or analyst

2.6. Sample Analysis Process

2.6.1. Envirolab Analysis

For sampling events CCWS01 to CCWS05, the analysis of samples collected in the Cudlee Creek bushfire area was conducted by the Adelaide office of Envirolab. This was required for the PAH samples given the complexity and equipment required for this analysis. Envirolab provided sampling bottle specifically for metals (Initial round pre-acidified) and for PAH and organic hydrocarbons. Samples were collected and kept on ice to keep temperature at 4°C (Duncan et al. 2007). Samples were either directly delivered to Envirolab or held overnight on ice due to the duration of sampling campaign. Chain of custody was directly handled on delivery of samples.

The suite of metals tested by Envirolab varied slightly between sampling events. The core suite of metals outlined in Table 1 was included each time, but additional metals such were also included in some sampling event, with the summary of tested metals in Table 13. The testing for PAHs was consistent, with the results for each of the PAHs listed in Table 2, as well as the total overall PAH in the sample.

Table 13: Summary of Metals Tested for Sampling Events

	CCWS01	CCWS02	CCWS03	CCWS04	CCWS05	CCWS06
Aluminium-Total	No	No	Yes	Yes	No	No
Arsenic-Total	Yes	Yes	Yes	Yes	Yes	Yes
Cadmium-Total	Yes	Yes	Yes	Yes	Yes	Yes
Chromium-Total	Yes	Yes	Yes	Yes	Yes	Yes
Cobalt-Total	No	Yes	Yes	Yes	No	No
Copper-Total	Yes	Yes	Yes	Yes	Yes	Yes
Iron-Total	No	Yes	Yes	Yes	No	No
Lead-Total	Yes	Yes	Yes	Yes	Yes	Yes
Manganese-Total	No	Yes	Yes	Yes	No	No
Mercury - Total	Yes	Yes	Yes	Yes	Yes	Yes
Molybdenum-Total	No	Yes	Yes	Yes	No	No
Nickel-Total	Yes	Yes	Yes	Yes	Yes	Yes
Selenium-Total	No	Yes	Yes	Yes	No	No
Strontium-Total	No	Yes	Yes	Yes	No	No
Uranium-Total	No	Yes	Yes	Yes	No	No
Vanadium-Total	No	Yes	Yes	Yes	No	No
Zinc-Total	Yes	Yes	Yes	Yes	Yes	Yes

2.6.2. Flinders Laboratory Analysis

Analysis through Envirolab meant that there were limits on the quantity of samples that could be collected for budgetary reasons. Samples from all locations were collected during CCWS05 and CCWS06 with the intention of using the Atomic Absorption Spectrometer (AAS) in the Flinders Laboratory to conduct metals analyses. A select range of samples from CCWS06 were tested both in the AAS and at Envirolab to validate ensure consistency of results. The AAS was run for searching for lead in samples, all of which came back below the limit of detection. This was consistent with the samples that were submitted to Envirolab.

2.7. Data Collection Frequency

2.7.1. Longitudinal Study Considerations

Critical to this research was the important element of this study that it was conducted longitudinally, as evidence from the literature review suggested that a single cross-sectional study of the sampling locations may be insufficient for assessment of the effect of the bushfire. Evidence from previous studies with multiple rounds of sampling conducted in post-bushfire areas found evidence that PAH levels in soils drop in the post-fire period, with the drop off significant in the first four months (Campos et al. 2019). Observations of water concentrations of PAH peaked slightly later, around 5 months after the bushfire event (Mansilha et al. 2019), before similarly declining. This could be a result mobilisation of PAHs into water requiring certain levels of rainfall runoff they enter the watercourse, and potentially that metals within the sediment may also experience peaks around this time due. These longitudinal studies had sampling events with initial frequencies of approximately 3-4 months, before becoming less frequent as the bushfire event moved further into the (Campos et al. 2019; Mansilha et al. 2019)

2.7.2. Longitudinal Design

The research area for this study was located in the Adelaide Hills, which are situated relatively close to the Adelaide metropolitan region. As such, the organisation of sampling events and collection of samples was not logistically onerous. Due to the timing of the beginning of this research, immediate sampling of the area post-fire was not collected. The first sampling event took place on 27 March 2020, just over 3 months post the ignition time of the Cudlee Creek bushfire, which raised the potential that some contaminant concentration had been lost due to runoff and streamflow.

Evidence from the observed rainfall in Figure 11 in the period between the Cudlee Creek bushfire and the first sample date however showed that only two large rainfall events had occurred in the intervening period. It seemed unlikely that contaminants had been completely missed, particularly as many sites in the first sampling round had ponded due to low water levels.

In order to ensure any potential contaminants were not missed in response to this, the second sampling event was decided to be conducted after the next large rainfall event.

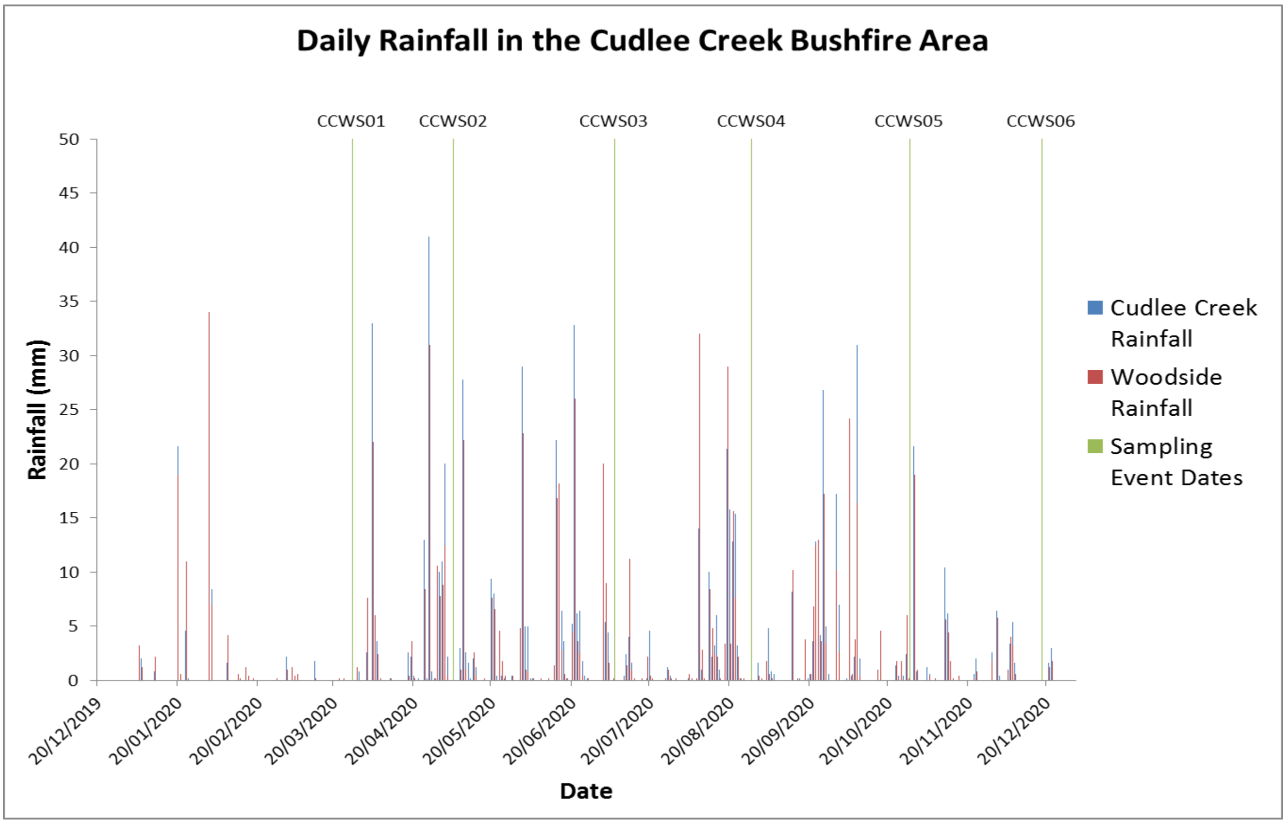


Figure 11: Cudlee Creek Bushfire Area Daily Rainfall (BoM 2021a, 2021b)

2.7.3. Sampling Frequency

For this purpose, 6 sampling events campaigns were undertaken in the course of this research. The first sampling event (Cuddle Creek Water Sampling 01, or CCWS01) occurred approximately 3 months after the Cudlee Creek bushfire. The results of the first sampling event showed little evidence of contaminant mobilisation, so the next sampling event was undertaken after the next large storm, which would likely see runoff generated and entering the watercourses. However, the next significant rainfall occurred 12 days after the first sampling event, which was deemed too close in proximity to conduct sampling again; the area was visited however (CCWS01b) to observe if there was any change in river flow and provide some additional material for the photo set data. The second sampling event (CCWS02) instead went ahead a little over a month later, after a period of significant rain in late April (Figure 11).

This also coincided with the time post fire when Mansilha et al. (2019) observed the peak PAH concentration in water, so this approach gave the best chance of capturing contaminant loads. After that event, a schedule of sampling once every two months was established.

Due to the extensive longitudinal nature of the research, sampling at a large number of sites was cost prohibitive. As such, the collection of data only occurred at a select number of locations at each sampling event. To ensure ongoing data from each sample site, the photo set was vital to maintain data collection from all sites.

2.8. Sampling Events

This section outlines the way in which this research was designed, sample sites were identified, data were handled and the way in which the longitudinal study was implemented. The result of this planning was the sampling campaigns outlined in Table 14.

Table 14: Sampling Summary

Event Title	Date Collected	Days between Sampling Events	Data Collected (No. Locations)
Cudlee Creek Water Sampling 01 (CCWS01)	27/03/2020	-	Metals (13) PAHs (10) Site Photos (16)
Cudlee Creek Water Sampling 01b (CCWS01b)	08/04/2020	12	Site Photos (16)
Cudlee Creek Water Sampling 02 (CCWS02)	05/05/2020	39 (CCWS01) 27 (CCWS01b)	Metals (14) PAHs (2) Site Photos (16)
Cudlee Creek Water Sampling 03 (CCWS03)	07/06/2020	62	Metals (2) Site Photos (16)
Cudlee Creek Water Sampling 04 (CCWS04)	28/08/2020	53	Metals (4) Site Photos (16)
Cudlee Creek Water Sampling 05 (CCWS05)	28/10/2020	61	Metals (16) PAHs (6) Site Photos (16)
Cudlee Creek Water Sampling 06 (CCWS06)	18/12/2020	51	Metals (16) Site Photos (18)

2.9. Methodological Limitations

As previously stated, the requirement to change the methods from sampling dams on properties to looking at watercourses did present some limitations as a proxy measure. Chief among these was the fact that watercourses are more likely to flush contaminate downstream, meaning that contaminants may quickly move out of the monitored area of the system. Additionally, while the increased capture of contaminants may result from larger catchment area, unaffected areas of the catchment may also contribute, diluting the effect of contaminants that may be stronger in dams that are wholly within the burnt area. Investigation of watercourses deeper into the CCFR were sought, however, due to the danger posed within the area due to tree instability, entry was not possible.

Additionally, cost limitations (particularly with PAH testing, which requires testing within a week) meant that sampling all sites in every round of sampling was infeasible. Key sites (particularly S02 and S04) that had experienced burning in their immediate vicinity were prioritised for testing with each round. This however did mean that there may have been effects that were missed in other areas.

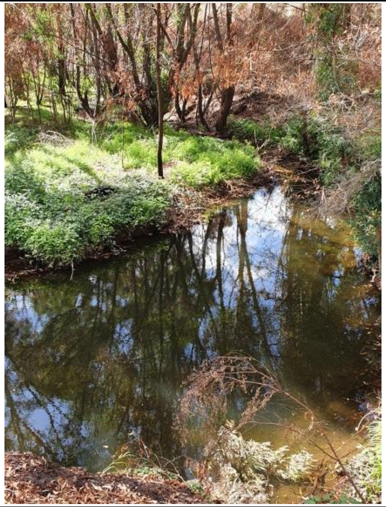
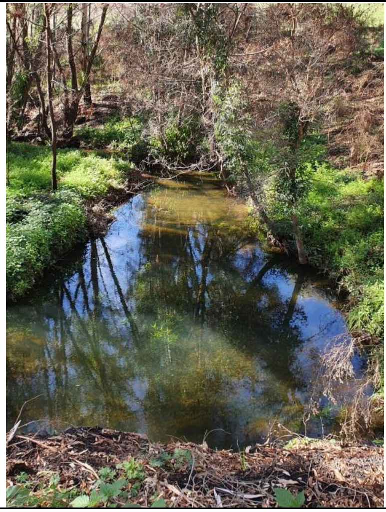
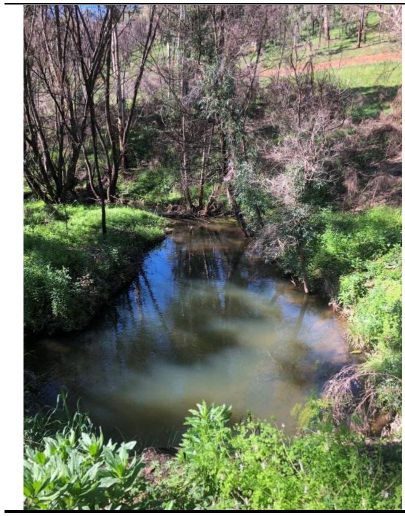
Finally, the variations in concentrations over the course of a longitudinal study require careful consideration before they are attributed to the influence of bushfires. Seasonal variations in flow and regrowth may have influence, and comparison to controls was important in this context. However, definitive attribution may be difficult, due to other external events.

3. RESULTS

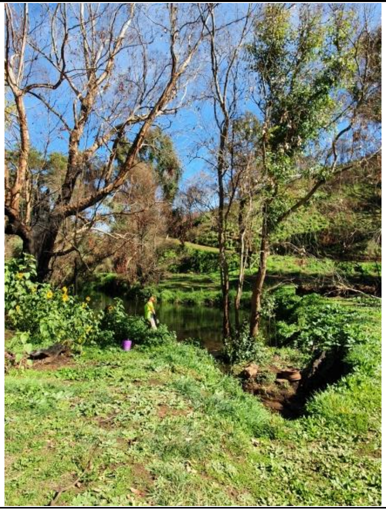
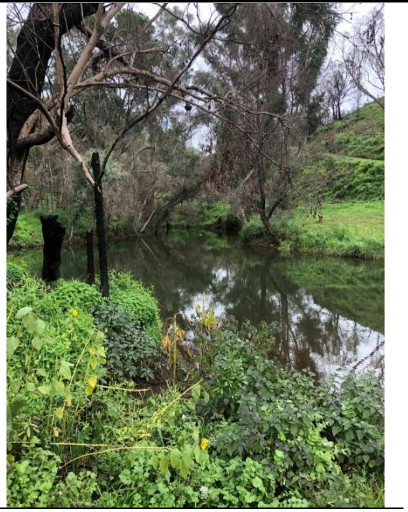
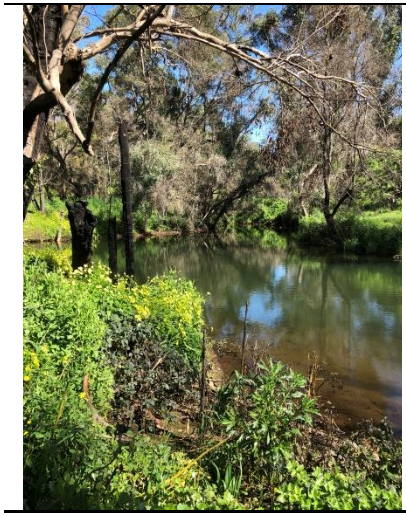
3.1. Selected Photo Sets

A photo set was kept of all sampling sites to observe the sample sites in the post-fire environment. A number of photo sets with interesting or important results were selected to provide context to the sampling events. Imagery of the remaining sampling sites was included in Appendix A1. Additional Photo Sets.

3.1.1. Sample Site S02

CCWS01b 08/04/2020	CCWS02 05/05/2020	CCWS03 06/07/2020	Comment
			Sample Site 02 (S02) was located in the River Torrens catchment, in the Fox Creek tributary. Fox Creek was the most prominent creek that ran through the CCFR. It was evident that this area that was subjected to severe burning based on the eucalypt population nearby. Evidence of burning in the canopy of the mid-sized trees in these photos is also evident. However, the riparian vegetation at this site was green and healthy from the sampling event CCWS01b, just over 3 months post-bushfire. Whether this was due to regrowth or protection afforded by proximity to the watercourse was unclear, although vegetation in photo foreground appeared burnt
CWS04 18/08/2020	**CCWS05 28/10/2020**	**CCWS06 25/12/2020**	
			

3.1.2. Sample Site S04

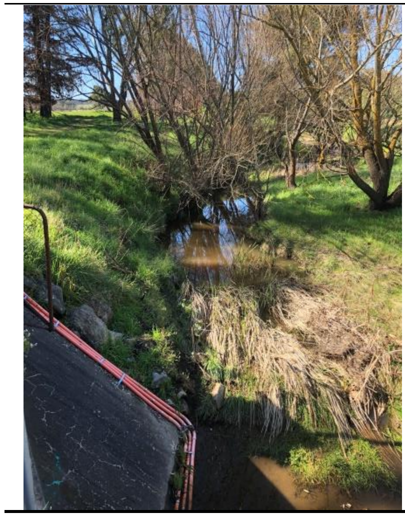
CCWS01 27/03/2020	CCWS02 05/05/2020	CCWS03 06/07/2020	Comment
			Sample Site 4 (S04) was located in the River Torrens catchment, in the Fox Creek tributary. This sample site was upstream from S02, located at the base of a hilled area of the CCFR. This was an important site as it received runoff from the most severely burnt part of the Cudlee Creek bushfire area. Water was ponded during the first sampling event due to low water level and outflow was generally low due to small and raised outflow channel so longer residence time of contaminants could be expected. Despite clear evidence of burning of surrounding trees, riparian vegetation is green with significant coverage just over 3 months post-bushfire, similar to S02.
CWS04 18/08/2020	**CCWS05 28/10/2020**	**CCWS06 25/12/2020**	
			

3.1.3. Sample Site S06

CCWS01b 08/04/2020	CCWS02 05/05/2020	CCWS03 06/07/2020
		
CWS04 18/08/2020	**CCWS05 28/10/2020**	**CCWS06 25/12/2020**
		

Commet: Sample Site 06 (S06) was located in the Onkaparinga River catchment on the Western Branch of the Onkaparinga River, in between Lobethal and Woodside. This area was used for livestock pasture and vineyards, in a relatively flat valley area. This area was important it was collected runoff from to moderate-severe burning of both agricultural land and forest areas nearby so had a variety of different possible contaminant sources.Despite the burning estimate from the ΔNBR, it was observed that there had been signifcant recovery of grasses, with the photo from CCWS01b showing green foliage. Whether this was due to proximity to watercourse was unclear, but not burned undergrowth was observed. Although there appeared to be less vegetative cover in the subsequent studies, recovery towards the end of the year suggested this was related to seasonal variation.

3.1.4. Sample Site S09

CCWS01 27/03/2020	CCWS02 05/05/2020	CCWS03 06/07/2020	Comment
NA			Sample Site 9 (S09) was located in the Onkaparinga River catchment on Inverbrackie Creek. Inverbrackie Creek runs through a mixed used horticulture, agriculture and rural residential area, with native woody vegetation within these areas. This site was important as it was the only site to record values of contaminants above the ADWG, with a high level of Mn reported, in addition to raise but not hazardous Fe, Sr and Zn. This area was fire affected as observed by the pines in the background of CCWS02. Unfortunately, imagery of this area was not captured in the initial sampling event, however despite burning very close to this area riparian vegetation appeared healthy.
CWS04 18/08/2020	**CCWS05 28/10/2020**	**CCWS06 25/12/2020**	
			

3.1.5. Control Site CS02

CCWS01 27/03/2020	CCWS02 05/05/2020	CCWS03 06/07/2020
		
CWS04 18/08/2020	**CCWS05 28/10/2020**	**CCWS06 25/12/2020**
		

Commet: Sample Site 02 was located in the River Torrens catchment, a tributary that joined the River Torrens from from the north, which meant its catchment wa not within the bushfire zone. Water from this tributary is discharged from the Millbrook Reservoir to the north. Other than the water level which was observed to vary between vistis, the habitat surrounding this control sample site seemed stable, and there was no evidence that ash deposition from the bushfire had occurred or was an issue at this location.

3.2. Trace Metal Results

3.2.1. Arsenic Results

Arsenic was tested for in all of the sampling events that were submitted to Envirolab, where there was detection limit 1 μg/L, with the safe water drinking limit 10 μg/L (Table 1). Arsenic was detected at a number of sampling locations, although concentrations did not exceed ADWG at any location (Table 15). Of note was that most samples taken from within the Torrens Catchment were below the limit of detection across every sampling campaign, while concentrations were measurable at every location tested in the Onkaparinga catchment, including the control sites.

Table 15: Arsenic Results (μg/L)

	CCWS01	CCWS02	CCWS03	CCWS04	CCWS05	CCWS06
S01	2	<dl	-	-	-	-
S02	<dl	<dl	<dl	<dl	-	<dl
S03	<dl	<dl	-	-	-	-
S04	<dl	<dl	<dl	<dl	-	<dl
S04B	-	-	-	<dl	-	<dl
S05	<dl	<dl	-	-	-	-
S06	4	2	-	-	-	-
S07	4	1	-	-	-	-
S08	2	1	-	-	-	1
S09	-	5	-	-	-	-
S10	-	-	-	3	-	-
S11	-	-	-	-	-	-
CS01	1	<dl	-	-	-	-
CS02	<dl	<dl	-	-	-	-
CS03	<dl	<dl	-	-	-	-
CS04	-	-	-	-	-	-
CS05	3	<dl	-	-	-	1
CS06	2	2	-	-	-	-

3.2.2. Cadmium Results

Cadmium was tested for in all of the sampling events that were submitted to Envirolab, where there was detection limit 0.1µg/L, with the safe water drinking limit 2µg/L (Table 1). Cadmium was below the limit of detection at every site tested (Table 16), in both the bushfire affected areas and control sites.

Table 16: Cadmium Results (µg/L)

	CCWS01	CCWS02	CCWS03	CCWS04	CCWS05	CCWS06
S01	<dl	<dl	-	-	-	-
S02	<dl	<dl	<dl	<dl	-	<dl
S03	<dl	<dl	-	-	-	-
S04	<dl	<dl	<dl	<dl	-	<dl
S04B	-	-	-	<dl	-	<dl
S05	<dl	<dl	-	-	-	-
S06	<dl	<dl	-	-	-	-
S07	<dl	<dl	-	-	-	-
S08	<dl	<dl	-	-	-	<dl
S09	-	<dl	-	-	-	-
S10	-	-	-	<dl	-	-
S11	-	<dl	-	-	-	-
CS01	<dl	<dl	-	-	-	-
CS02	<dl	<dl	-	-	-	-
CS03	<dl	<dl	-	-	-	-
CS04	-	-	-	-	-	-
CS05	<dl	<dl	-	-	-	<dl
CS06	<dl	<dl	-	-	-	-

3.2.3. Copper Results

Copper was tested for in all of the water samples that were submitted to Envirolab, where there was detection limit 1 µg/L, with the safe water drinking limit 2000 µg/L and an aesthetic limit of 1000 µg/L (Table 1). Low concentrations of copper were detected, well below any hazardous levels (Table 17). Detection occurred most often in the second sample campaign, with all tested samples in the Onkaparinga River catchment above the limit of detection, but was still very low.

Table 17: Copper Results (µg/L)

	CCWS01	CCWS02	CCWS03	CCWS04	CCWS05	CCWS06
S01	<dl	<dl	-	-	-	-
S02	<dl	<dl	2	<dl	-	<dl
S03	2	5	-	-	-	-
S04	<dl	<dl	<dl	<dl	-	<dl
S04B	-	-	-	<dl	-	<dl
S05	2	1	-	-	-	-
S06	<dl	3	-	-	-	-
S07	<dl	2	-	-	-	<dl
S08	<dl	2	-	-	-	-
S09	-	2	-	-	-	-
S10	-	-	-	3	-	-
S11	-	-	-	-	-	<dl
CS01	2	<dl	-	-	-	-
CS02	3	<dl	-	-	-	-
CS03	3	<dl	-	-	-	-
CS04	-	-	-	-	-	-
CS05	1	<dl	-	-	-	<dl
CS06	2	2	-	-	-	-

3.2.4. Chromium Results

Chromium was tested for in all of the metals samples that were submitted to Envirolab, where there was detection limit 1 μg/L, with the safe water drinking limit 50 μg/L (Table 1). Very minimal concentrations of chromium were detected, well below any hazardous levels (Table 18). No significant pattern was observed in the locations where concentration was above the detectible limited.

Table 18: Chromium Results (μg/L)

	CCWS01	CCWS02	CCWS03	CCWS04	CCWS05	CCWS06
S01	<dl	<dl	-	-	-	-
S02	<dl	<dl	<dl	<dl	-	<dl
S03	<dl	<dl	-	-	-	-
S04	<dl	<dl	<dl	<dl	-	<dl
S04B	-	-	-	<dl	-	<dl
S05	1	<dl	-	-	-	-
S06	<dl	1	-	-	-	-
S07	<dl	<dl	-	-	-	-
S08	<dl	<dl	-	-	-	<dl
S09	-	1	-	-	-	-
S10	-	-	-	<dl	-	-
S11	-	<dl	-	-	-	-
CS01	2	<dl	-	-	-	-
CS02	<dl	<dl	-	-	-	-
CS03	<dl	<dl	-	-	-	-
CS04	-	-	-	-	-	-
CS05	<dl	<dl	-	-	-	<dl
CS06	<dl	<dl	-	-	-	-

3.2.5. Lead Results

Lead was tested for in all of the metals samples that were submitted to Envirolab where there was a detection limit 1µg/L. The AAS at the Flinders University laboratory was also used to test samples collected for CCWS04, CCWS05 and CCWS06 for lead, with concentration reliably detectable to at least 125 µg/L. Concentrations below this were considered not detected (nd) to distinguish these results from those from Envirolab.

The ADWG limit for Lead was 10 µg/L (Table 1). Very few sites had lead concentrations above limit of detection, aside from CS06 where lead was detected both times the area was sampled, although neither was above ADWG limits (Table 19). Comparison of the results from Envirolab with those observed in the AAS was made difficult by all results being below detection limits; however, this indicated that the results are not inconsistent between both sets of testing.

Table 19: Lead Results (µg/L)

	CCWS01	CCWS02	CCWS03	CCWS04	CCWS05	CCWS06
S01	<dl	<dl	-	-	nd	nd
S02	<dl	<dl	<dl	<dl, nd	nd	<dl,nd
S03	<dl	<dl	-	-	nd	nd
S04	<dl	<dl	<dl	<dl, nd	nd	<dl, nd
S04B	-	<dl	-	<dl, nd	nd	<dl, nd
S05	1	<dl	-	-	-	-
S06	<dl	<dl	-	-	nd	nd
S07	<dl	<dl	-	-	nd	<dl, nd
S08	<dl	<dl	-	-	nd	nd
S09	-	1	-	-	nd	nd
S10	-	-	-	<dl, nd	nd	nd
S11	-	-	-	-	-	<dl,nd
CS01	2	<dl	-	-	nd	nd
CS02	<dl	<dl	-	-	nd	nd
CS03	<dl	<dl	-	-	nd	nd
CS04	-	-	-	-	-	-
CS05	<dl	<dl	-	-	nd	nd
CS06	6	2	-	-	-	-

3.2.6. Manganese Results

Manganese was not tested for in all metals samples submitted to Envirolab, with the metals suite not including manganese in results from CCWS01 and CCWS05. The Envirolab detection limit for manganese was 5 µg/L, with the ADWG limit 500 µg/L and the aesthetic limit 100 µg/L (Table 1). Manganese was detected at all sites, however was below ADWG limits in all locations except for S09 during CCWS02, which recorded a level 5 times the ADWG limit (other sites recorded levels above the aesthetic limit during this sampling event including S01, S06, CS03 and CS05) (Table 20). This high level of manganese is discussed later.

Table 20: Manganese Results (µg/L)

	CCWS01	CCWS02	CCWS03	CCWS04	CCWS05	CCWS06
S01	-	130	-	-	-	-
S02	-	23	44	32	-	-
S03	-	54	-	-	-	-
S04	-	53	18	31	-	-
S04B	-	-	-	89	-	-
S05	-	64	-	-	-	-
S06	-	110	-	-	-	-
S07	-	73	-	-	-	-
S08	-	29	-	-	-	-
S09	-	2500	-	-	-	-
S10	-	-	-	73	-	-
S11	-	-	-	-	-	-
CS01	-	41	-	-	-	-
CS02	-	39	-	-	-	-
CS03	-	140	-	-	-	-
CS04	-	-	-	-	-	-
CS05	-	290	-	-	-	-
CS06	-	46	-	-	-	-

3.2.7. Mercury Results

Mercury was tested for in all of the metals samples that were submitted to Envirolab, where there was detection limit 0.05 µg/L, with the safe water drinking limit 1 µg/L (Table 1). Mercury concentrations were found to be below the limit of detection at all sample locations for each sampling event (Table 21).

Table 21: Mercury Results (µg/L)

	CCWS01	CCWS02	CCWS03	CCWS04	CCWS05	CCWS06
S01	<dl	<dl	-	-	-	-
S02	<dl	<dl	<dl	<dl	<dl	-
S03	<dl	<dl	-	-	-	-
S04	<dl	<dl	<dl	<dl	<dl	-
S04B	-	-	-	<dl	<dl	-
S05	<dl	<dl	-	-	-	-
S06	<dl	<dl	-	-	-	-
S07	<dl	<dl	-	-	-	-
S08	<dl	<dl	-	-	<dl	-
S09	-	<dl	-	-	-	-
S10	-	-	-	<dl	-	-
S11	-	-	-	-	-	-
CS01	<dl	<dl	-	-	-	-
CS02	<dl	<dl	-	-	-	-
CS03	<dl	<dl	-	-	-	-
CS04	-	-	-	-	-	-
CS05	<dl	<dl	-	-	<dl	-
CS06	<dl	<dl	-	-	-	-

3.2.8. Nickel Results

Nickel was tested for in all of the metals samples that were submitted to Envirolab, where there was detection limit 1 µg/L, with the safe water drinking limit 20 µg/L (Table 1). Nickel concentrations were found to be below the limit of detection at most locations, with only a few low level results (Table 22).

Table 22: Nickel Results (µg/L)

	CCWS01	CCWS02	CCWS03	CCWS04	CCWS05	CCWS06
S01	<dl	2	-	-	-	-
S02	<dl	<dl	<dl	<dl	<dl	-
S03	<dl	2	-	-	-	-
S04	<dl	<dl	<dl	<dl	<dl	-
S04B	-	-	-	<dl	<dl	-
S05	1	2	-	-	-	-
S06	<dl	1	-	-	-	-
S07	2	1	-	-	-	-
S08	<dl	<dl	-	-	1	-
S09	-	3	-	-	-	-
S10	-	-	-	2	-	-
S11	-	-	-	-	-	-
CS01	1	<dl	-	-	-	-
CS02	<dl	<dl	-	-	-	-
CS03	<dl	<dl	-	-	-	-
CS04	-	-	-	-	-	-
CS05	1	1	-	-	<dl	-
CS06	<dl	<dl	-	-	-	-

3.2.9. Zinc Results

Zinc was tested for in all of the metals samples that were submitted to Envirolab where there was detection limit 1 µg/L, with no set ADWG health limit but an aesthetic limit of 3000 µg/L (Table 1). Zinc concentrations were generally observed either very low or below detectable limits, with the exception S09 in CCWS02, where zinc concentration was an order of magnitude larger than at any other (Table 23). Regardless, the significance of this result was low, as the concentration was still another order of magnitude lower than the aesthetic limit.

Table 23: Zinc Results (µg/L)

	CCWS01	CCWS02	CCWS03	CCWS04	CCWS05	CCWS06
S01	<dl	3	-	-	-	-
S02	<dl	2	<dl	2	<dl	-
S03	7	4	-	-	-	-
S04	<dl	2	<dl	<dl	<dl	-
S04B	-	-	-	1	<dl	-
S05	2	6	-	-	-	-
S06	3	13	-	-	-	-
S07	<dl	11	-	-	-	-
S08	5	20	-	-	2	-
S09	-	340	-	-	-	-
S10	-	-	-	5	-	-
S11	-	-	-	-	-	-
CS01	4	2	-	-	-	-
CS02	<dl	6	-	-	-	-
CS03	3	<dl	-	-	-	-
CS04	-	-	-	-	-	-
CS05	1	2	-	-	1	-
CS06	<dl	2	-	-	-	-

3.3. PAH Results

PAHs samples were collected during three of the sampling events, CCWS01, CCWS02 and CCWS06. Samples were collected for 8 bushfire locations and 2 control locations in CCWS01, with 2 locations in CCWS02, and 6 samples collected for CCWS06. Samples from the sites on Fox Creek within the CCFR, S02 and S04, were tested in all three of these sampling events to capture longitudinal impacts. PAH testing was conducted by Envirolab on the PAH compounds listed in Table 2. The results of PAH testing are shown in Table 24, where the results for all PAHs at each sample location were condensed into measure of total PAH, due to the fact that no PAH compounds were detected for any location at a detection limit of 1 µg/L. These results were consistent across bushfire and control locations in both catchments.

Table 24: Total PAH Results Summary

Sample Site	Total PAH		
	CCWS01	CCWS02	CCWS06
S01	<dl	-	-
S02	<dl	<dl	<dl
S03	<dl	-	-
S04	<dl	<dl	<dl
S04B	-	-	<dl
S05	<dl	-	-
S06	<dl	-	-
S07	<dl	-	<dl
S08	<dl	-	<dl
S11	-	-	<dl
CS02	<dl	-	-
CS05	<dl	-	-

4. DISCUSSION

4.1. Trace Metals Discussion

4.1.1. Overview of Results

Previous studies of contamination in the post bushfire in watercourse environment have identified a number of potential metals that may be affected by remobilisation and present a risk to watersheds. Of particular concern in the literature was the remobilisation of arsenic and mercury. Concerns about the mobilisation of mercury were based on the loss of concentration in the soil, indicating it had been redistributed in the catchment (Campos et al. 2015). If this mercury mobilisation occurred in the Cudlee Creek bushfire area, it is likely that the mobilisation into watercourses was either not significant or occurred before the sampling of the area was undertaken, as mercury was below the detection limit at every sampling location.

There was some evidence that the Cudlee Creek bushfire may have correlated with an increased arsenic concentration in the watercourse. During the first survey CCWS01, concentrations of arsenic in the Onkaparinga catchment at sampling locations S06, S07 and S08 of between 2-4 µg/L were observed; although, the control site CS05 also had a similar recorded level of arsenic concentration (3 µg /L). The similar levels of arsenic concentration observed at control site CS05 made meant it was unclear if the levels of arsenic concentration observed at S06, S07, S08 was due to the Cudlee Creek bushfire, or related to the land use in the catchment. Subsequent sampling in CCWS02 showed that these increased levels of arsenic concentration initially observed in these locations declined over time, (1-2 µg/L, with the previous untested S09 having a higher 5 µg/L; the results from S09 area discussed further below) but observable levels of arsenic remained. There was concern in the region regarding arsenic contamination related to copper chrome arsenate (CCA) treated wood ash, which is often used for fence posts and outdoor furniture (Spinks et al. 2006) but testing by the EPA on a dam in the area yielded only very low levels of copper, chromium and arsenic (EPA SA, DEW & PIRSA 2020). A majority of concentrations of arsenic found in bushfire affected rainwater tanks by Spinks et al. (2006) appeared to be in a similar range, which may indicate an influence of bushfire on the observed levels of arsenic concentrations. In any event, however, the degree to which the increased levels of arsenic concentration observed are a concern is uncertain, given the concentrations were below the ADWG, and well below concentrations hazardous to livestock (ANZECC & ARMCANZ 2000).

Concentrations of various other metals of concern (cadmium, chromium, copper, lead, nickel and zinc) were largely found to either be below detectable limits or very low with respect to ADWG in all sampling events, with the exception of S09 in Inverbrackie Creek, which had concentrations of manganese above ADWG in the CCWS02 sampling event.

Previous monitoring in the River Torrens catchment area had been conducted by the Environmental Protection Authority South Australia, as part of the ongoing monitoring of South Australia's rivers and streams. A location just upstream of the sampling sites used in this thesis was repeatedly sampled over a two year period between 1995-1997, with the water tested for aluminium, copper, iron, lead and zinc (EPA SA 1998). The metals concentration levels observed by the EPA SA (1998) report were all considered moderate to good in terms of water quality, and the results obtained by the post-bushfire sampling in this thesis were consistently within the previously observed confidence interval. This suggested that the bushfire had not caused concentrations of these metals atypical for the region.

4.1.2. Inverbrackie Creek

The watercourse sampled at S09 was Inverbrackie Creek, part of the Onkaparinga River catchment located near the town of Woodside. The sample collected at S09 as part of the CCWS02 sampling event was the only sample containing a concentration of metals which exceeded the Australian Water quality standard for health, with the concentration of manganese observed at 2500 µg/L, which is five times the ADWG limit. In addition, elevated concentrations (relative to other sampled sites) of iron, strontium and zinc were observed. The concentration of arsenic was observed to be 5 µg/L, which was much higher than the concentrations at other sample points in the CCWS02 sampling event, although this concentration of arsenic is still below the ADWG. These elevated concentrations were of interest due to the fact that all of these elements, other than strontium, have been associated with post-bushfire contamination in water (Smith et al. 2011b). In particular, bushfire has been shown to increase manganese and iron concentrations into watercourses (White et al. 2006), which suggested that the increased levels of iron and manganese may have been as a result of contaminant mobilisation from upstream areas discharging metal loads into the watercourse.

However, Inverbrackie Creek runs near land owned Bird-in-Hand Gold Project, a proposed subsurface gold mine in the Woodside area. As part of an environmental investigation related to this project, Terramin (2016) conducted an environmental study on water quality parameters near the area of the proposed mining project, approximately a kilometre upstream from S09. The results of that study found that Manganese in the downstream area was frequently above the ANZECC threshold concentration for species protection, at times reaching nearly 5000 µg/L on the downstream side of the property. This monitoring also found that there were periods of significant iron, arsenic and zinc concentration increases, which meant the results found at S09 were not atypical for this watercourse. This was strong evidence that this elevated level of Manganese was unlikely to be related to the Cudlee Creek bushfire, but instead was related to some other function of the creek, speculated to be phosphorous loads (Terramin 2016). This also meant that the concentrations of other metals at S09 could not be evaluated with certainty with respect to bushfire influence. Results from the other sample sites in the Onkaparinga River catchment did not exhibit these concentrations, which indicated that Inverbrackie Creek was not representative of the area.

4.1.3. Metals in Forest Catchments

Two of the sample sites (S02 and S04) were targeted as potential sentinel sites for bushfire related metals mobilisation due to their high risk characteristics, namely they were located in the CCFR which was the area most severely burnt in the bushfire, they were in an area with steeper slopes, meaning that there was greater potential for runoff, and they were part of a majority forested catchment, meaning greater potential for remobilised contaminants. These two sites were also close to CCFR fence lines, which were destroyed during the fire, potentially exposing these locations to another contaminant. However, the results obtained at these two sites were almost uniformly below the limits of detection. In CCWS02, when a majority of the sites in the bushfire area were tested, concentration of iron (see Appendix A2.3 Table 27) at these two sites were the lowest recorded of any sampling site. Given that these sites were selected due to their assumed greater risk of exposure to trace metals, the significant lack of metals concentrations at these sites was worthy of consideration. A number of potential reasons for these results were considered

4.1.3.1. Metal Concentrations in the Cudlee Creek Area

It was possible that concentrations of metals in the CCFR were very low naturally, and that the levels entering into the watercourse capable of detection remained too low, even with sediment remobilised by fire. However, given the literature suggested that eucalypts were a significant sink for trace metals, and given the scale and intensity of the fire in the CCFR, it appears unlikely that the collective metals concentration of these trees was insignificant.

4.1.3.2. Missed sampling window

It was possible that metals concentrations were low due to intense burning creating significant amounts of sediment, which was quickly eroded into the Fox Creek area and flushed through the watercourse before the first sampling event was conducted. The time between the Cudlee Creek bushfire and the commencement of this research was approximately three months (for clarity, the proposal of this research was considered in early March 2020). In this period of time, it may have been possible for this runoff to occur. This seemed unlikely, however, given that only two significant rainfall events occurred within that period, with the greatest recorded rainfall in the Cudlee Creek region in that period being over 20mm of rain (Figure 11). The rainfall in Cudlee Creek was quite low in the months between the end of December 2019 and March 2020 in comparison to historical data analysed for previous years (Figure 12). While not impossible, it seemed unlikely that the runoff generated from these two rainfall events was sufficient. Additionally, photography from CCWS01 (Figure 13) and CCWS01b (see Results Section 3.1.1) showed that these sites were ponded, which indicated that there was not significant flow and that retaining concentrations of contaminant s from sediments would be more likely.

4.1.3.3. Lack of Runoff

From another perspective, it was possible that the lack of rain observed in the Cudlee Creek region meant that there was minimal contaminant runoff, and that regrowth of low lying shrubs in the region commenced the process of refixing metals into the soil. The recovery of the low lying vegetation was observed to be quick in the area, particularly in the riparian zones around the water sampling locations. The ponding at S02 was noted to be exceptionally clear during the first sampling event, which indicated that there was little suspended sediment at that time.

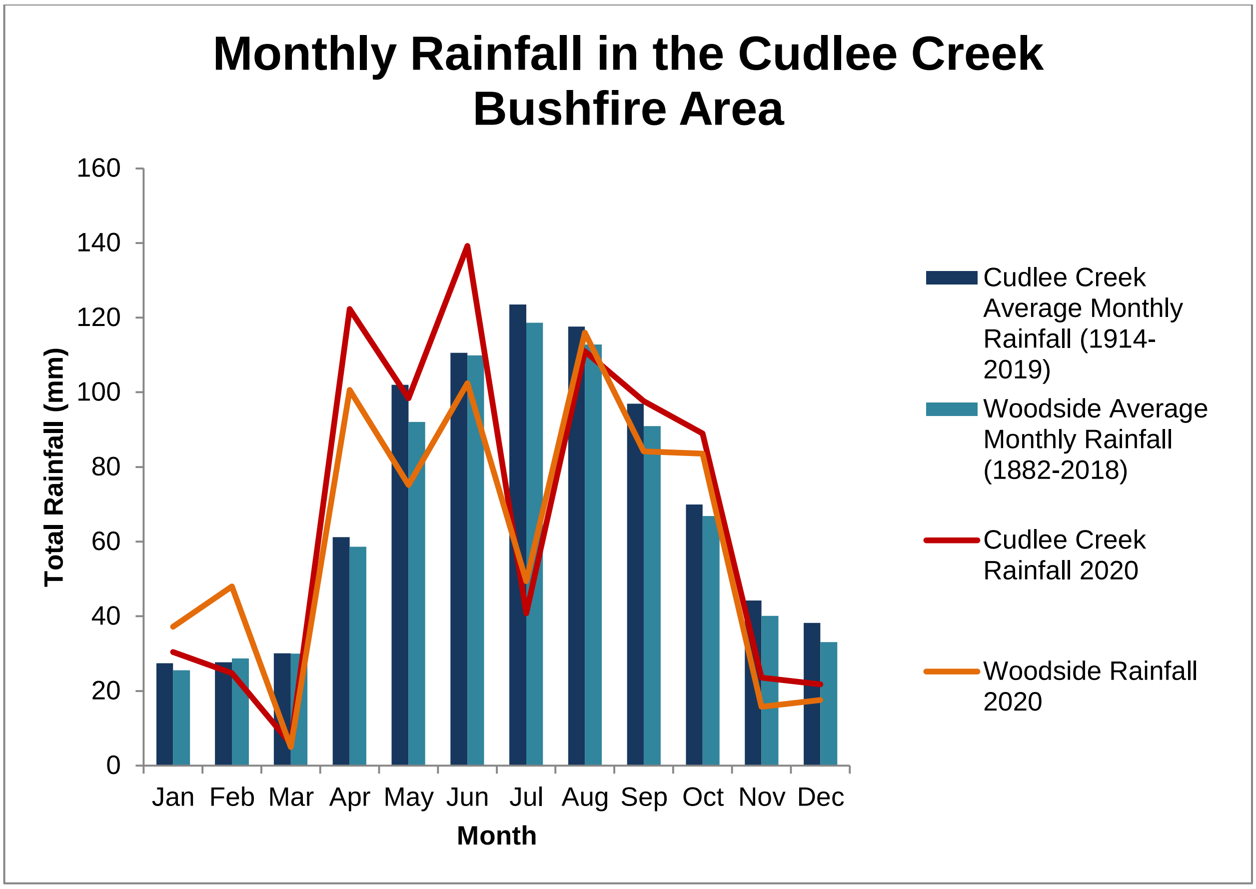


Figure 12: Monthly Rainfall in the Cudlee Creek Bushfire Area (BoM 2019, 2021a, 2021b)

Figure 13: Ponding at 02 during CCWS01

4.1.3.4. Riparian Vegetation Protection

Similarly, with the riparian vegetation observed around the locations (see Results Sections 3.1.1 and 0), it was apparent that it either recovered very quickly or was not burnt in the bushfire. The ongoing existence around the watercourse could potentially have filtered the incoming sediments. Research has suggested that the riparian vegetation can be protected from bushfires due to their proximity to a water source and different moisture contents (Pettit & Naiman 2007). Additionally, the disparity in burnt areas between the hill slopes and trees in the valley near the watercourse was apparent, as seen in Figure 9.

4.1.4. Comparison of Catchment Land Cover/Land Use

As identified in the first section of this report, the two catchments in which this metals sampling took place had differing land cover, with significantly more native vegetation in the River Torrens catchment than the Onkaparinga catchment. This difference was further exacerbated by the fact that the sampling locations in the River Torrens catchment were largely in the most forested region, while the Onkaparinga River catchment sampling locations were more adjacent to farm or residential areas. Most concentrations of metals however did not appear to have any bias towards either catchment, with the possible exception of arsenic, as previously mentioned with respect to the cases of S06, S07, S08. The correlation between S06 and S07 was not unexpected, given they both were located on the Western Branch of the Onkaparinga River. All of these locations had large agricultural and rural residential areas in the watershed, which may indicate proximity to areas more likely to be treated with CCA does raise the possibility of bushfire contamination.

4.1.5. Summary

Whatever the reasons for the low concentration of metals observed at S02 and S04, it was clear that overall the results of metals testing did not provide a strong indication of metal mobilisation. Arsenic measurements at S05, S06 and S07 during CCWS01 and CCWS02 may have been correlated, but the lack of data from a more proximate time after the bushfire means this is unclear. Remobilisation of metals due to bushfire was considered a significant concern to the health of watercourses in the literature, and a potential risk to drinking water. The results from this research have not shown any marked impact on the concentrations of metals due to the Cudlee Creek bushfire.

4.2. PAH Discussion

4.2.1. Overview of Results

The results of the PAH testing in the Cudlee Creek bushfire area indicated that none of the PAHs identified in Table 2 were present in concentration above the detection limit. This was not unexpected, as the detection limit for PAHs in the analysis conducted was 1μg/L. Previous testing of PAHs in watercourses after bushfire has generally found concentrations of individual PAH compounds to be 2-3 orders of magnitude smaller than this limit, while total levels of PAHs were still an at least 1 order of magnitude smaller (Mansilha et al. 2019; Olivella et al. 2006; Schafer et al. 2010). Even research with lower limits of detection have not detected PAHs (Ross et al. 2018), and polluted waters rarely have concentrations that exceed 1 μg/L (Zhang et al. 2019).

This presents some concern given the ADWG level of toxicity for BaP is at 0.01 μg L, which was well below the detection limit of the testing in this study. Additionally, based on the relative toxicity scale in Table 2, BaB, BbF, BjF, BkF, DahA and Ind could potentially pose a threat to human health but be below the detection limit (BghiP and Chr may be edge cases). As there existed potentially hazardous contaminants below the testing detection limit, care had to be taken in the conclusions that could be drawn about PAHs in the catchment. A definitive judgement on whether PAH concentrations increased as a result of the Cudlee Creek bushfire could not be made, other than concluding that PAH concentrations did not increase to levels that would be considered extremely high in water.

4.2.2. PAHs in the Context of the Cudlee Creek Bushfire

From looking at the other results in the study, however, it was possible to gain an insight into the impact that any presence of PAHs had on the watercourses studied. The results of metals analysis showed that there was not a significant increase in concentrations, which provided an indication that the mobilisation of contaminants due to runoff in the post-bushfire environment of this study area may not be particularly high. This can be considered similar for PAHs, although mobilisation pathways for PAHs are slightly different to metals, in that there is a greater influence of distribution due to ash and wind erosion, which even as a sediment is more likely to be subject to runoff. Additionally, the photo sets of the sample locations showed no evidence of toxicity, with no evidence of biota harm or impacts to regrowth. On the contrary, riparian vegetation regrowth appeared to be extremely healthy.

Additionally, based on the literature, it is likely that by the final round of sampling a significant portion of any PAHs that were potentially generated by the bushfire and entered into the watercourses would likely have either been washed away, volatised into the air or adsorbed onto sediments. If harm to the environment was not observed in the time of peak concentrations (being 1 to 5 months post fire), it is unlikely that PAHs in flowing water in the area are presently hazardous.

4.2.3. Summary

Although PAHs are considered a potential risk to water environment, this research has shown that their observation can be difficult, and that using proxy measures of environmental health may be necessary to establish the impact they have on the environment. The evidence from the discussion of the mobilisation of metals in the Cudlee Creek area pointed towards mobilisation being relatively low. If a similar conclusion can be made regarding the PAHs, that would indicate that watercourses in the region likely did not have significant concentrations of PAHs entering as a result, meaning that the harm caused and risk to human water supply was low.

4.3. Photo Set Discussion

4.3.1. Overview of Photo Set

The photo set was a qualitative measure that was included in this research to give context and to provide results where water sampling was not able to provide information. This evidence gathered within this photo log was crucial to the interpretation of results of the mobilisation of metals and PAHs. The evidence from this was largely focussed on the details that the photo log could provide about the sampling site, primarily through inspection of the riparian vegetation.

4.3.2. Riparian Vegetation in the Cudlee Creek Bushfire Area

As discussed previously, the riparian vegetation around the sampling locations is one of the potential factors that may have led to reduction in contaminated sediment entering into the waterways. This was particularly noticeable for the sample sites in the CCFR, where in the initial sampling events the devastation to the eucalypts and taller trees was obvious (Figure 9). However, in contrast, the riparian vegetation in the locations accessible for sampling was observed to be green and appeared to be thriving. As the first sampling event took place three months after the bushfire started in that area, it was not clear whether the riparian vegetation had been protected due to its proximity to the water body, or whether it had quickly regrown. Visual inspection of the sampling sites suggested that fire had affected the upper reaches of the surrounding trees, and some lower lying vegetation appear to have been fire damaged (see Results Sections 3.1.1 and 0).

Regardless of the fate of the riparian vegetation in the immediate aftermath of the fire, there was extant native vegetation three months post-fire, during which time there had only been two rainfall events that may have generated runoff. This suggested that the watercourse, at least at these locations, was well protected from sediment, as riparian vegetation holds together the banks of these watercourses, and can also act as a sink for incoming sediments.

4.3.3. Summary

As a conclusion relating the metals mobilisation due to the Cudlee Creek bushfire not immediately apparent, and the results from PAH testing not sufficient to rule out potential hazards, the photo set was effective in providing evidence to clarify the qualitative data. The importance of the photo set cannot be underestimated in its role of providing critical context and evidence for conclusions, and its inclusion demonstrated the importance of the situational context when discussing qualitative results.

4.4. Research Implications

This research has found that Cudlee Creek bushfire has not resulted in significant mobilisation of metals into the watercourses. This has been supported by the evidence from the South Australian EPA which conducted testing on at least one dam that was located near CCA treated timber, but was found not to contain Cu, Cr or As levels that would be hazardous to livestock (EPA SA, DEW & PIRSA 2020).

The research finds itself a place within the growing body of literature that has focussed on the consequences of the Black Summer bushfires. Many of these studies have focussed on the effect on biota in the watercourse, although study has been hampered by COVID-19 restrictions. A significant focus has been directed towards ash sediment induced fish death (Joehnk et al. 2020; Reis-Santos & Gillanders 2020). The quantity of ash generated in these bushfires seemed to have a far greater impact than in Cudlee Creek. Reis-Santos and Gillanders (2020) found evidence of fish mortality along the banks when surveying 4 months after the fires on Kangaroo Island. No evidence of biota mortality due to sediments was observed anywhere at the locations sampled.

This, coupled with the results of low metals mobilisation and the absence of evidence of significant PAH contamination, has meant that it appeared that the watercourses in the area of the Cudlee Creek bushfire have escaped significant harm, and that the conditions in Cudlee Creek show no indication of long term damage. This may have implications in the future for understanding how serious contamination of watercourses occurs.

4.5. Further Research

4.5.1. Research in Cudlee Creek

This thesis has touched on a number of important factors regarding the influence of bushfire in mobilising contaminants into watercourse. It has provided a solid background for contaminant measures in the Cudlee Creek bushfire area as the area returns to normal. Further research in the area affected by the Cudlee Creek bushfire would be beneficial, to build on this research and track the long term implications of the fire. ΔNBR modelling of the bushfire area over the course of the year since the bushfire has indicated that much of the land cover has established itself Figure 14; however, severe burn scars remain in the CCFR, meaning that the potential for mobilisation of those soils still exists. As mentioned in the literature review, evidence suggests that the full impact of bushfire is not necessarily felt for years. ΔNBR imagery shows that while much of the area affected by Cudlee Creek bushfire have seen surface coverage of vegetation return, the areas of severe burning in the CCFR area continue to be impacted as a result of the bushfire. Given that the intensity of the fire in this area has meant that the soil has been so thoroughly burnt that no vegetation has returned is concerning and warrants further study.

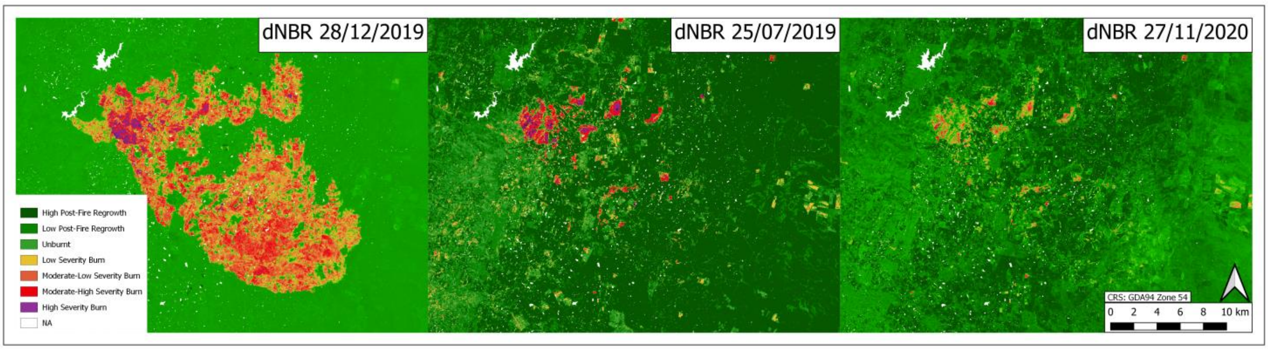


Figure 14: Cudlee Creek Post-Fire ΔNBR Comparison

4.5.2. Rural Residential Dam Testing

One of the more relevant areas that have the potential to yield informative results is the testing of the effects of fire on mobilisation of metals and PAHs into rural residential dams. This research was designed partly as a way to approximate the effect that bushfire induced mobilisation would have on these areas, hence the consideration of ADWG when discussing the concentrations of contaminants. However, it was acknowledged that this comparison is not direct; factors such as watershed size, slope and riparian vegetation are likely quite different in typical dams. Future research on dams would build on this research and provide important information to those who use dams in bushfire prone regions and advance the knowledge of relationship of bushfires to PAHs and metals.

4.5.3. Riparian Vegetation

This discussion has focussed extensively on the fact that riparian vegetation is potentially one of the reasons that there has been reduced metals mobility entering into the watercourses after the bushfire. The role that riparian vegetation plays is well documented in the literature, but the specific role of filtering bushfire induced mobilisation would build from this research.

4.5.4. The Role of Eucalypt Species

A number of studies in the literature have used eucalypts as the primary tree study of choice. However study of the metal retention and bushfire response of *Eucalyptus obliqua* would be warranted given the questions over metals mobilisation in the *Eucalyptus obliqua* dominated CCFR.

4.6. Study Limitations

4.6.1. PAH Detection Limit

As previously discussed, the detection limit used in testing the PAHs in the samples collected in this research did not identify concentrations of individual or total PAHs. While this testing excluded the possibility of extreme contamination and conclusions were still able to be drawn from this research, for greater robustness more knowledge of the concentrations of PAHs was required. The conclusions drawn between the mobilisation of metals and PAHs have greater weight if quantifiable evidence was able to show a relationship. The fact that ADWG estimated hazardous levels for a number of PAHs were below the threshold that this research was able to conduct is a significant impediment to assessment as to whether the Cudlee Creek bushfire affected PAHs and the implications for water safety, regardless of other indicators.

4.6.2. Timing of First Sampling Event

Another limitation of this research is the fact that the first sampling event took place three months after the initial fire event. Although the multiple sampling round conducted in this research added great robustness to the quality of results and was useful in tracking the impact on the local watercourse environment, this three month gap meant that a lot of potential data went uncollected. Information about the severity of burning at the sample locations, the recovery of riparian vegetation, ash and sediment deposit in the aftermath of the bushfire, as well as metals and PAH testing was not collected in a period that can be when the most extreme and hazardous conditions to the watercourse occur. This was unavoidable and the first sampling event took place as soon was practically possible; however crucial data was not captured that may have given greater context as to why relatively low contaminant results were found.

5. CONCLUSION

This research was conducted with two main aims: to determine whether the concentrations of metals and PAHs in the watercourse were affected by the Cudlee Creek bushfire event, and to determine whether any change in concentration has affected the potential safety of potable water in the Cudlee Creek area. Based on the evidence collected in this report, there was insufficient evidence to suggest the watercourses as a result of the Cudlee Creek bushfire have experienced significant contamination. Within the forest catchment around CCFR, plant biota had returned and riparian vegetation did not show evidence of contamination or poor ecosystem health. Sampling of watercourses did not detect raised PAH levels, while nearly all metals detected were within ADWG. The only detection of metals that was not within ADWG was in an area that had exhibited historically similar concentrations of metals, indicating that this result was not likely to be related to the bushfire.

While this research has proven useful and should be of relief to those who use and live around the Cudlee Creek bushfire area, these results should be considered a stepping stone for further research to gain more useful knowledge in relation to the effect of bushfires on watercourses. Analysis of storage dams on rural properties, which have less ecological resistance to entering contaminants, would be a natural next step in revealing this body of knowledge.

The conclusion of this research was that while there may have been some bushfire induced increases in watercourses of metals, the effect has not been of any significant concern in the Cudlee Creek area. The way in which the watercourses in the Cudlee Creek catchments have responded to the bushfire indicated that the pathways metals and PAHs use to enter watercourses have not been sufficiently impacted by the bushfire to significantly alter concentrations of contaminants in the water, and particularly given the passage of time since the bushfire event.

As such, while other effects of the Cudlee Creek bushfire may be ongoing, there is no evidence to suggest that there has been any detrimental impact on the safety or quality of potable water as a result of the Cudlee Creek bushfire.

The wider implications for other bushfire affected areas are less clear; evidence from other areas affected by Black Summer bushfires indicate that these areas experienced significant ash flow as sediment, which has affected other water quality parameters, leading to adverse outcomes which threaten water safety. Understanding the reasons why bushfire induced sediment mobilisation was devastating in some bushfire affected areas but not in others is an important area for further research.

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APPENDIX A: ADDITIONAL RESULTS

A1. Additional Photo Sets

This appendix catalogues the imagery of sampling sites that was not included in the main report. Note that photo sets of earlier sampling events were not as comprehensive, so representative imagery was limited.

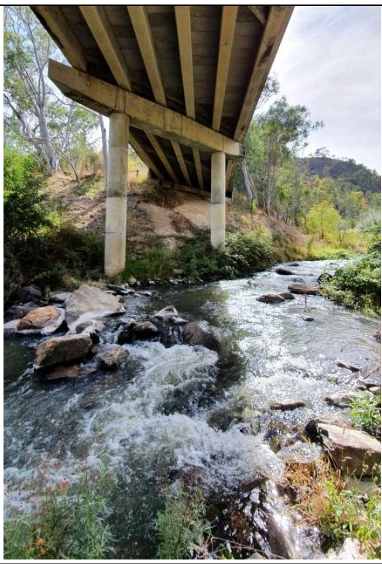
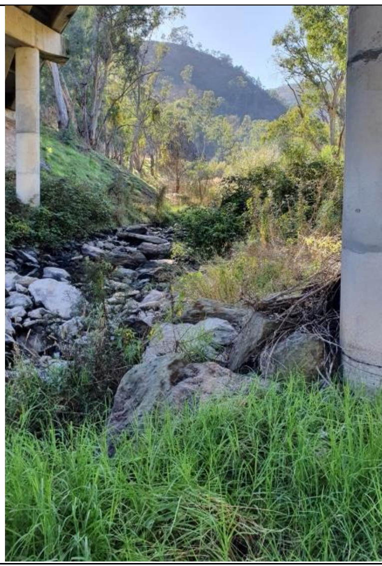
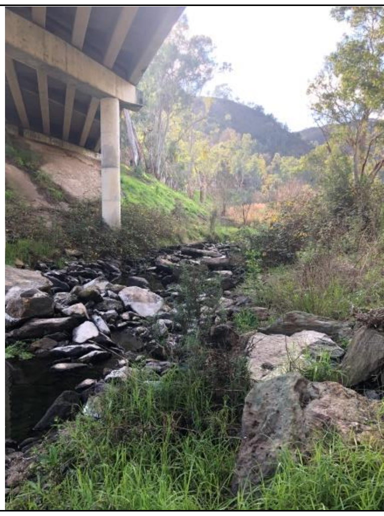
A1.1. Control Site 1 Photo Log

Control Site 1 (CS01) Photo Log	
CCWS01 27/03/2020	**CCWS02 05/05/2020**
	
CCWS03 06/07/2020	**CCWS04 18/08/2020**
	
CCWS05 28/10/2020	**CCWS06 25/12/2020**
	

A1.2. Control Site 2 Photo Log

Control Site 2 (CS02) Photo Log	
CCWS01b 08/04/2020	CCWS02 05/05/2020
	
CCWS03 06/07/2020	CCWS04 18/08/2020
	
CCWS05 28/10/2020	CCWS06 25/12/2020
	

A1.3. Control Site 3 Photo Log

Control Site 3 (CS03) Photo Log	
CCWS01 27/03/2020	**CCWS02 05/05/2020**
	
CCWS03 06/07/2020	**CCWS04 18/08/2020**
	
CCWS05 28/10/2020	**CCWS06 25/12/2020**
	

A1.4. Control Site 4 Photo Log

Control Site 4 (CS04) Photo Log	
CCWS01 27/03/2020	**CCWS02 05/05/2020**
	
CCWS03 06/07/2020	**CCWS04 18/08/2020**
	
CCWS05 28/10/2020	**CCWS06 25/12/2020**
	

A1.5. Control Site 5 Photo Log

Control Site 5 (CS05) Photo Log	
CCWS01 27/02/2020	CCWS02 05/05/2020
	
CCWS03 06/07/2020	CCWS04 18/08/2020
	
CCWS05 28/10/2020	CCWS06 25/12/2020
	

A1.6. Control Site 6 Photo Log

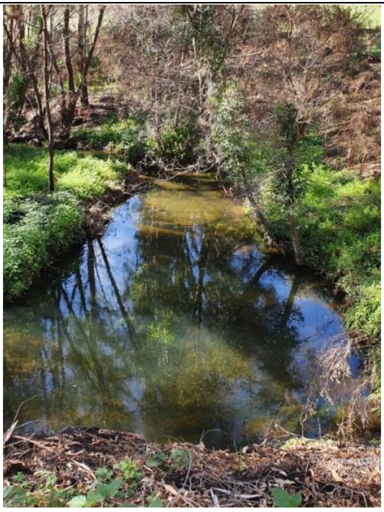
Control Site 6 (CS06) Photo Log	
CCWS01 27/03/2020	**CCWS02 05/05/2020**
	
CCWS03 06/07/2020	**CCWS04 18/08/2020**
NA	
CCWS05 28/10/2020	**CCWS06 25/12/2020**
	

A1.7. Sample Site 1 Photo Log

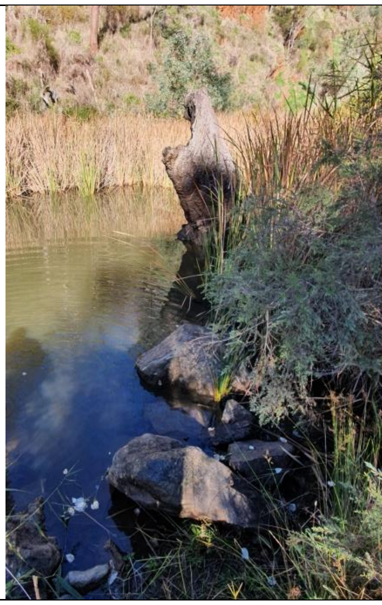
Sample Site 1 (S01) Photo Log

CCWS01 27/03/2020	CCWS02 05/05/2020
	
CCWS03 06/07/2020	**CCWS04 18/08/2020**
	
CCWS05 28/10/2020	**CCWS06 25/12/2020**
	

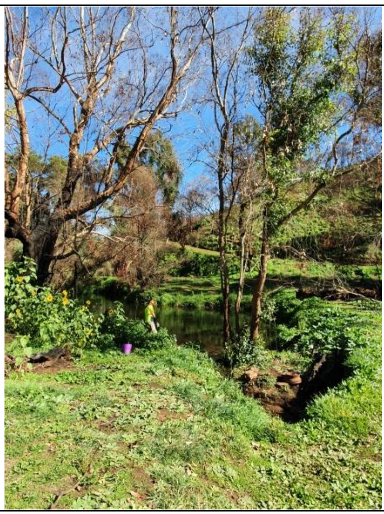
A1.8. Sample Site 2 Photo Log

Sample Site 2 (S02) Photo Log	
CCWS01b 08/04/2020	**CCWS02 05/05/2020**
	
CCWS03 06/07/2020	**CCWS04 18/08/2020**
	
CCWS05 28/10/2020	**CCWS06 25/12/2020**
	

A1.9. Sample Site 3 Photo Log

Sample Site 3 (S03) Photo Log	
CCWS01 27/03/2020	**CCWS02 05/05/2020**
	
CCWS03 06/07/2020	**CCWS04 18/08/2020**
	
CCWS05 28/10/2020	**CCWS06 25/12/2020**
	

A1.10. Sample Site 4 Photo Log

Sample Site 4 (S04) Photo Log	
CCWS01 27/03/2020	CCWS02 05/05/2020
	
CCWS03 06/07/2020	CCWS04 18/08/2020
	
CCWS05 28/10/2020	CCWS06 25/12/2020
	

A1.11. Sample Site 4B Photo Log

Sample Site 4B (S04B) Photo Log	
CCWS01 – CCWS03	**CCWS04 18/08/2020**
NA	
CCWS05 28/10/2020	**CCWS06 25/12/2020**
	

A1.12. Sample Site 5 Photo Log

Sample Site 5 (S05) Photo Log	
CCWS01 27/03/2020	CCWS02 05/05/2020
	
CCWS03 06/07/2020	CCWS04 18/08/2020
	
CCWS05 28/10/2020	CCWS06 25/12/2020
	

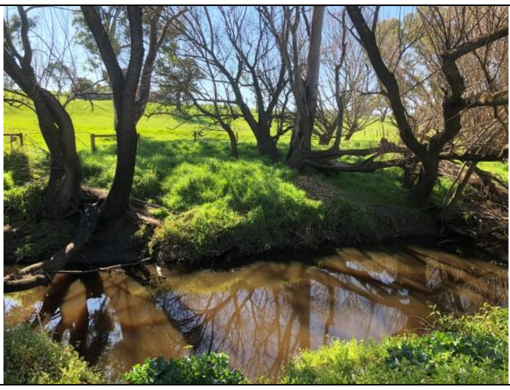
A1.13. Sample Site 6 Photo Log

Sample Site 6 (S06) Photo Log	
CCWS01 27/03/2020	**CCWS02 05/05/2020**
	
CCWS03 06/07/2020	**CCWS04 18/08/2020**
	
CCWS05 28/10/2020	**CCWS06 25/12/2020**
	

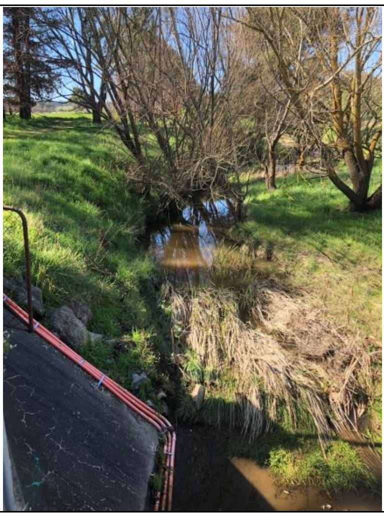
A1.14. Sample Site 7 Photo Log

Sample Site 7 (S07) Photo Log	
CCWS01 27/03/2020	**CCWS02 05/05/2020**
	
CCWS03 06/07/2020	**CCWS04 18/08/2020**
	
CCWS05 28/10/2020	**CCWS06 25/12/2020**
	

A1.15. Sample Site 8 Photo Log

Sample Site 8 (S08) Photo Log	
CCWS01 27/03/2020	**CCWS02 05/05/2020**
	
CCWS03 06/07/2020	**CCWS04 18/08/2020**
	
CCWS05 28/10/2020	**CCWS06 25/12/2020**
	

A1.16. Sample Site 9 Photo Log

Sample Site 9 (S09) Photo Log	
CCWS01 27/03/2020	**CCWS02 05/05/2020**
NA	
CCWS03 06/07/2020	**CCWS04 18/08/2020**
	
CCWS05 28/10/2020	**CCWS06 25/12/2020**
	

A1.17. Sample Site 10 Photo Log

Sample Site 10 (S10) Photo Log	
CCWS01-CCWS02 NA	
CCWS03 06/07/2020	**CCWS04 18/08/2020**
	
CCWS05 28/10/2020	**CCWS06 25/12/2020**
	

A1.18. Sample Site 11 Photo Log

Sample Site 11 (S11) Photo Log
CCW01-CCWS05 NA
CCWS06 25/12/2020


A2. Results for Miscellaneous Metals

A2.1. Aluminium Analysis

- Envirolab Detection Limit: 10 μg/L
- Safe Drinking Water Limit: not set, aesthetic limit of 200 μg/L (NHMRC & NRMMC 2021)
- Elevated levels: Yes, above aesthetic limit CCWS04-S10

Table 25: Aluminium Analysis Results (μg/L)

	CCWS01	CCWS02	CCWS03	CCWS04	CCWS05	CCWS06
S01	-	-	-	-	-	-
S02	-	-	120	77	-	-
S03	-	-	-	-	-	-
S04	-	-	58	37	-	-
S04B	-	-	-	81	-	-
S05	-	-	-	-	-	-
S06	-	-	-	-	-	-
S07	-	-	-	-	-	-
S08	-	-	-	-	-	-
S09	-	-	-	-	-	-
S10	-	-	-	230	-	-
S11	-	-	-	-	-	-
CS01	-	-	-	-	-	-
CS02	-	-	-	-	-	-
CS03	-	-	-	-	-	-
CS04	-	-	-	-	-	-
CS05	-	-	-	-	-	-
CS06	-	-	-	-	-	-

A2.2. Cobalt Analysis

- Envirolab Detection Limit: 1µg/L
- Safe Drinking Water Limit: not stated in NHMRC and NRMMC (2021)
- Elevated levels: Unlikely, all results around or below detection limit

Table 26: Cobalt Analysis Results (µg/L)

	CCWS01	CCWS02	CCWS03	CCWS04	CCWS05	CCWS06
S01	-	<dl	-	-	-	-
S02	-	<dl	<dl	<dl	-	-
S03	-	<dl	-	-	-	-
S04	-	<dl	<dl	<dl	-	-
S04B	-	-	-	<dl	-	-
S05	-	<dl	-	-	-	-
S06	-	<dl	-	-	-	-
S07	-	<dl	-	-	-	-
S08	-	<dl	-	-	-	-
S09	-	3	-	-	-	-
S10	-	-	-	1	-	-
S11	-	<dl	-	-	-	-
CS01	-	<dl	-	-	-	-
CS02	-	<dl	-	-	-	-
CS03	-	<dl	-	-	-	-
CS04	-	-	-	-	-	-
CS05	-	1	-	-	-	-
CS06	-	<dl	-	-	-	-

A2.3. Iron Analysis

- Envirolab Detection Limit:10 µg/L
- Safe Drinking Water Limit: not set, aesthetic limit of 300 µg/L (NHMRC & NRMMC 2021)
- Elevated levels: Yes, results in many sample locations above aesthetic limits

Table 27: Iron Analysis Results (µg/L)

	CCWS01	CCWS02	CCWS03	CCWS04	CCWS05	CCWS06
S01	-		-	-	-	-
S02	-	100	380	310	-	-
S03	-	710	-	-	-	-
S04	-	150	80	89	-	-
S04B	-	-	-	350	-	-
S05	-	1100	-	-	-	-
S06	-	1200	-	-	-	-
S07	-	930	-	-	-	-
S08	-	470	-	-	-	-
S09	-	2500	-	-	-	-
S10	-	-	-	810	-	-
S11	-	-	-	-	-	-
CS01	-	300	-	-	-	-
CS02	-	1000	-	-	-	-
CS03	-	200	-	-	-	-
CS04	-	-	-	-	-	-
CS05	-	790	-	-	-	-
CS06	-	1000	-	-	-	-

A2.4. Molybdenum Analysis

- Envirolab Detection Limit:1µg/L
- Safe Drinking Water Limit: 50µg/L (NHMRC & NRMMC 2021)
- Elevated levels: No, all either at or below limit of detection

Table 28: Molybdenum Analysis Results (µg/L)

	CCWS01	CCWS02	CCWS03	CCWS04	CCWS05	CCWS06
S01	-	<dl	-	-	-	-
S02	-	<dl	<dl	<dl	-	-
S03	-	1	-	-	-	-
S04	-	<dl	<dl	<dl	-	-
S04B	-	-	-	<dl	-	-
S05	-	<dl	-	-	-	-
S06	-	<dl	-	-	-	-
S07	-	<dl	-	-	-	-
S08	-	<dl	-	-	-	-
S09	-	<dl	-	-	-	-
S10	-	-	-	<dl	-	-
S11	-	-	-	-	-	-
CS01	-	<dl	-	-	-	-
CS02	-	<dl	-	-	-	-
CS03	-	<dl	-	-	-	-
CS04	-	-	-	-	-	-
CS05	-	<dl	-	-	-	-
CS06	-	<dl	-	-	-	-

A2.5. Selenium Analysis

- Envirolab Detection Limit: 1µg/L
- Safe Drinking Water Limit: 10 µg/L (NHMRC & NRMMC 2021)
- Elevated levels: Mainly below limit of detection, CCWS02-CS05 near drinking water limit

Table 29: Selenium Analysis Results (µg/L)

	CCWS01	CCWS02	CCWS03	CCWS04	CCWS05	CCWS06
S01	-	<dl	-	-	-	-
S02	-	<dl	<dl	<dl	-	-
S03	-	<dl	-	-	-	-
S04	-	<dl	<dl	<dl	-	-
S04B	-	-	-	<dl	-	-
S05	-	<dl	-	-	-	-
S06	-	<dl	-	-	-	-
S07	-	<dl	-	-	-	-
S08	-	<dl	-	-	-	-
S09	-	<dl	-	-	-	-
S10	-	-	-	<dl	-	-
S11	-	<dl	-	-	-	-
CS01	-	<dl	-	-	-	-
CS02	-	<dl	-	-	-	-
CS03	-	<dl	-	-	-	-
CS04	-	-	-	-	-	-
CS05	-	8	-	-	-	-
CS06	-	<dl	-	-		-

A2.6 Strontium Analysis

- Envirolab Detection Limit: 1 µg/L
- Safe Drinking Water Limit: not stated in NHMRC and NRMMC (2021). 1500 µg/L Health Reference Level (US EPA 2014)
- Elevated levels: No

Table 30: Strontium Analysis Results (µg/L)

	CCWS01	CCWS02	CCWS03	CCWS04	CCWS05	CCWS06
S01	-	290	-	-	-	-
S02	-	180	110	120	-	-
S03	-	170	-	-	-	-
S04	-	200	87	91	-	-
S04B	-	-	-	110	-	-
S05	-	210	-	-	-	-
S06	-	130	-	-	-	-
S07	-	100	-	-	-	-
S08	-	49	-	-	-	-
S09	-	470	-	-	-	-
S10	-	-	-	220	-	-
S11	-	-	-	-	-	-
CS01	-	230	-	-	-	-
CS02	-	120	-	-	-	-
CS03	-	150	-	-	-	-
CS04	-	-	-	-	-	-
CS05	-	470	-	-	-	-
CS06	-	70	-	-	-	-

A2.7. Uranium Analysis

- Envirolab Detection Limit: 0.5 µg/L
- Safe Drinking Water Limit: 17 µg/L (NHMRC & NRMMC 2021)
- Elevated levels: No. Value of 2 µg/L at CS05 during CCWS02 unexpected, could be a result of phosphate fertilisers used on agricultural land adjacent to watercourse or previous mining in the area (NHMRC & NRMMC 2021).

Table 31: Uranium Analysis Results (µg/L)

	CCWS01	CCWS02	CCWS03	CCWS04	CCWS05	CCWS06
S01	-	<dl	-	-	-	-
S02	-	<dl	<dl	<dl	-	-
S03	-	<dl	-	-	-	-
S04	-	<dl	<dl	<dl	-	-
S04B	-	-	-	<dl	-	-
S05	-	<dl	-	-	-	-
S06	-	<dl	-	-	-	-
S07	-	<dl	-	-	-	-
S08	-	<dl	-	-	-	-
S09	-	<dl	-	-	-	-
S10	-	-	-	0.5	-	-
S11	-	-	-	-	-	-
CS01	-	0.5	-	-	-	-
CS02	-	<dl	-	-	-	-
CS03	-	<dl	-	-	-	-
CS04	-	-	-	-	-	-
CS05	-	2	-	-	-	-
CS06	-	<dl	-	-	-	-

A2.8. Vanadium Analysis

- Envirolab Detection Limit: 1 µg/L
- Safe Drinking Water Limit: not stated (NHMRC & NRMMC 2021)
- Elevated levels: No

Table 32: Vanadium Analysis Results (µg/L)

	CCWS01	CCWS02	CCWS03	CCWS04	CCWS05	CCWS06
S01	-	<dl	-	-		-
S02	-	<dl	<dl	<dl	-	-
S03	-	1	-	-	-	-
S04	-	<dl	<dl	<dl	-	-
S04B	-	-	-	<dl	-	-
S05	-	1	-	-	-	-
S06	-	3	-	-	-	-
S07	-	2	-	-	-	-
S08	-	1	-	-	-	-
S09	-	3	-	-	-	-
S10	-	-	-	3	-	-
S11	-	-	-	-	-	-
CS01	-	1	-	-	-	-
CS02	-	<dl	-	-	-	-
CS03	-	<dl	-	-	-	-
CS04	-	-	-	-	-	-
CS05	-	5	-	-	-	-
CS06	-	1	-	-	-	-