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A review on surface enhanced experimental catchments to improve farm water security and resilience in a drying climate in southwestern Australia

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Abstract

In this paper, the evolution of runoff enhancement treatments on both natural and artificial (or roaded) catchments used for rainfall harvesting to supply small on-farm dams in south-western Australia is reviewed. Over the last seven decades, various experimental treatments and approaches to enhance water shedding or harvesting techniques have been tested and adapted across this region to account for variations in slope, soil type and rainfall distribution. These adaptations are vital to maintain water harvesting efficiency and water security in a drying climate and enable farmers to continue to produce crops and support livestock effectively while increasing their climate resilience. As such, water security is one of the most important components of any agricultural enterprise. The treatments or sealants evaluated, varied in their capacity, cost, durability or water shedding capability, to provide a robust response to changes experienced in rainfall patterns, their intensity and frequency due to climate change. This review has highlighted the potential to use various surface treatments to increase the water harvesting efficiency from different landscapes in semi-arid or dryland agricultural areas in southwestern Australia.

Keywords: Artificial Catchments; Australia; Climate Resilience; Dryland Agriculture; Rainfall; Water Harvesting; Water Security

INTRODUCTION

Drylands- including semi arid areas- now cover 41% of the earths land mass (Yao *et al*., 2020). They are characterised by a scarcity of water, where precipitation is balanced by evapotranspiration, are highly vulnerable to climate change and impacts from human activities (UNEP, 2011; Huang *et al*., 2016). Notably, dryland zones support over two billion people, providing a large proportion of the food and fibre consumed globally (IUCN, 2019). The IPCC (2019) expects these regions to expand, based on global heating trends in the coming decades creating a need for rural communities, agricultural production systems and biodiversity to rapidly adapt.

Rainfall in these regions is often irregular and dispersed, varying in both temporal and spatial distribution as well its intensity and duration (Oweis *et al*., 2012; Stroosnijder *et al*.; 2012; Baek and Coles, 2013a). Weather extremes (e.g., floods, droughts) often significantly impact these regions agricultural production capability and the soils from which this productivity is derived (Coles, 2012; Coles and Baek, 2012; Yazar and Ali, 2017)

In Australia, a majority of crop and livestock production occurs in dryland or rainfed conditions (Anderson *et al*., 2016). In these conditions the average annual rainfall for cropping systems ranges between 300-600mm (as opposed to rangelands <300mm) - see Fig. 1. Farming

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operations in these dryland regions, where water supply reliability can be a limiting factor, requires both high quality and low-quality water. In practice, higher quality water is used for domestic purposes and farm operations such as crop spraying, with lower quality water used for livestock (Coles *et al*., 2000). As such, water security is one of the most important components of any agricultural enterprise (He *et al*., 2014). Within this context, the ability to capture or harvest more water from the landscape to improve productive resilience in an industry facing an increasingly drying climate becomes critical (Yazar and Ali, 2017).

Rainwater harvesting techniques therefore provide an alternative that has been the focus of cross-disciplinary studies in recent years (Vohland and Barry, 2009; Coles *et al*., 2011; Oweis *et al*., 2012; Mekdaschi Studer and Liniger, 2013; Patle *et al*., 2020). Using water harvesting techniques such as rainwater collecting systems (RCSs), for example roof rainfall-runoff collecting systems (RRCSs) for domestic use, and artificial catchment rainfall-runoff collecting systems (ACRCSs) linked to earth dams for agricultural uses, have many advantages as sustainable resilient water supplies (Baek and Coles, 2013a).

In southwestern Australia (circled area in Fig. 1) water security remains a significant issue, even though with water deficiency declarations made during the 1970's, 80's and 90's provided the impetus to develop a coordinated approach to water resource management between the Government and the rural community (Coles *et al*., 2000). During this period, the State Government invested $A2.6M to counter the impacts of drought or water

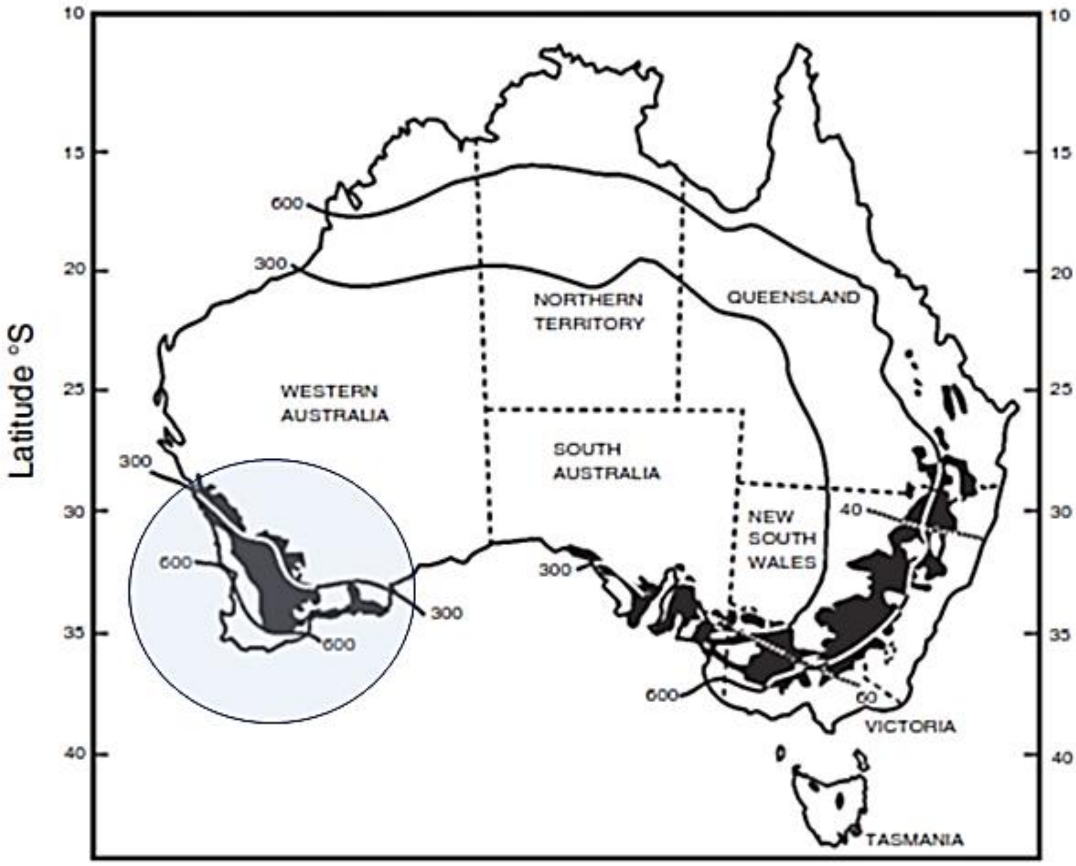


Fig. 1. Dryland cropping zones in Australia between the 300 and 600mm rainfall isohyets. All cropping zones in Western Australia receive >60 % of rainfall in the winter months. The improved catchment research to improve water harvesting capacity and supply reliability undertaken in the area circled are reviewed in this paper (Anderson *et al*., 2011) For more detail see Figure 4

deficiency (78% of which was spent on hauling water). A significant cost to the State. To counter problems of reliability both on and off-farm an integrated, structured, and planned approach to water harvesting and storage was recommended.

Roaded or improved catchments, dam storages and roof-raintank systems would play a pivotal role in delivering this water security, and therefore improved drought resilience leading to increased productivity. While it is acknowledged that there is significant global literature on water harvesting, this article is limited to reviewing the key innovations and evolution of runoff enhancement treatments in south-western Australia using data from 11 experimental catchments and town dam sites undertaken over the last seven decades.

APPROACH AND ANALYSIS

To improve drought resilience and productivity, following on from the water deficiency declaration in the later part of the 20th Century, it became apparent that if on-farm water supplies can be made reliable they are a practical and economic alternative to expensive piped water schemes. Most dryland farms in south western Australia rely almost exclusively on water supplies developed on-farm.

To overcome deficiencies in rainfall-runoff generation, building artificial catchments that are designed harvest rainwater from one area to divert it to another or into a storage system (e.g., earth dam or tank) has been know for millennia (Oweis *et al*., 2012). Roaded or compacted earthen catchments (Fig. 2) increase the runoff for a given rainfall event by: increasing the slope of the surface; decreasing surface detention; and reducing the surface permeability (i.e., compaction or sealing) of that sloping surface (Stanton, 2005).

The first initial steps taken toward improving the water harvesting capability of natural catchments to enhance the reliability of dams in southern WA was carried out by the public works department in 1949 (PWD, 1959). Later data collected from experimental catchments, (Laing, 1975. 1981; DAWA, 1980; Lanzke and Prince, 2004; Lantzke and Stanton, 2005; Short and Lantzke, 2006; Philpott *et al*., 2007; Baek and Coles, 2013b) supported the intuitive observation that the amount of runoff generated from natural catchments is rainfall intensity dependent, with runoff only being generated from both natural and artificial after a particular threshold was reached (Coles *et al*., 2011; Beek and Coles, 2011). The efficiencies of ACRCs, as well as various designs, soil types and batter slopes, to generate runoff from rainfall events in southwestern Australia has been evaluated over the last seven decades.

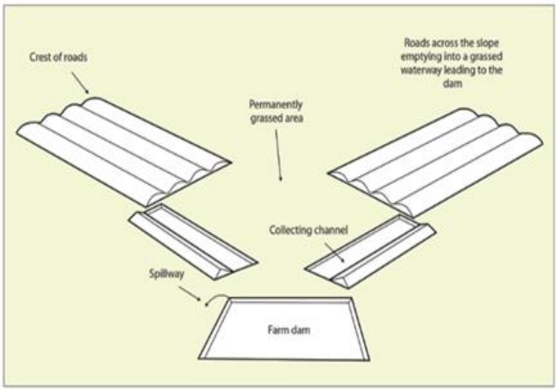


Fig. 2. An example an artificial catchment in landscapes with slopes greater than 1:80 where a stable waterway is present. Roads are constructed across the slope and empty into a grassed waterway that discharges into the dam (Stanton, 2005)

Data from 11 field experimental sites in this region is presented in Table 1. Each site deploys various surface enhancement treatments to improve the runoff efficiency. These efficiencies are compared with natural and compacted earth catchments to demonstrate the shift in either runoff threshold[1] or percentage of runoff generated, which provides an efficiency rating for each treatment type and design.

[1] The runoff threshold based on the total rainfall required during an event to generate runoff within a 24-hr period.

Table 1 (a-c). The runoff response from 102 experimental improved catchments using different enhanced runoff options from 11 trial sites in south-western Australia between 1949 and 2012

Trial Site	Year	Length of Record (Yrs)	Soil Types	Treatment Type	Area (ha)	Batter Slopes (%)	Runoff %
Lake Grace[a]	1949	6	Loamy sand over clay	Scraped and compacted with roller. Later bituminised	0.8094		25.3
Kulin[a]***	1950	3	Loamy sand over clay	Scraped and compacted with roller.	40.47	7	28.4
Narrogin[a] ***	1953	1	Loamy sands and clay	Scraped and compacted with roller.	60.705	7	35
Dalwallinu[a]***	1950	1	Loamy sands and clay	Scraped and compacted with roller.	40.47	7	21.8
Frankland Vineyards [dc,d,f,g]							
Plot Trial A (x3)	2003	1	Compacted clay	Control	0.02		24~
Plot Trial B (x3)	2003	1	Compacted clay	Calcium Lignosulphonate (Dustex)	0.02		43~
Plot Trial C (x3)	2003	1	Compacted clay	TGC (Reynolds Product)	0.02		51~
South Stirlings[i]*** **(24 plots)**							
x3	1971-73	3	Deep grey sand over yellow clay at between 45-80 centimetres. Some coarse iron gravels above the clays.	Shell water proofing oil	0.070		22.11
x3	1971-73	3		Shell water proofing oil +Colas	0.070		33.22
x3	1971-73	3		Terolas in top 2 cm of soil, rolled +Terolas	0.070		26.60
x3	1971-73	3		Diluted Terolas (1:#) + Terolas	0.070		14.92
x3	1971-73	3		Furnace fuel oil (diluted with distillate)	0.070		28.79
x3	1971-73	3		Transported and compacted clay	0.070		13.04
x3	1971-73	3		Transported and compacted clay with mini-roading	0.070		11.78
x3	1971-73	3		Control - no treatment (sandy soil)	0.070		6.19

Table 1 (b).

Trial Site	Year	Length of Record (Yrs)	Soil Types	Treatment Type	Area (ha)	Batter Slopes (%)	Runoff %	Threshold (T) mm
Newdegate[i]	1974	6	Sand over clay	Compacted Clay. Later bituminised	3.6		31.5	8.63
Wongan Hills[b] **(24 Plots)**								
4x	1975	5	Wongan Loamy Sand-Coarse loamy sand to 1.2m with soft FE nodules below that depth.	Compacted Earth-roller (x6)	0.012	12	43.3	3.61
4x	1975	5		Earth with double roller compacted (12x)	0.012	12	42.3	3.78
4x	1975	5		One coat bitumen on compacted earth	0.012	12	64.7	1.87
4x	1975	5		one coat fuel oil	0.012	12	76.3	1.20
4x	1975	5		Two Coat bitumen	0.012	12	88.9	0.45
4x	1975	5		Two Coat bitumen + Compaction gravel	0.012	12	89.9	0.52
4x	1975	5		Clay-covered RC	0.012	12	35	1.07

Table (c).

Trial Site	Year	Length of Record (Yrs)	Soil Types	Treatment Type	Area (ha)	Batter Slopes (%)	Threshold (T) mm
Merredin[h] (16 Plots)							
4x	2006	2		Control-Compacted Earth	0.055	33	7.89
4x	2006	2		Compacted +Acrylic Polymer-soluble soil binder -Total Ground Cover (SL)	0.055	33	5.02
4x	2006	2	Loamy sand, clays and combination of clays and loamy sands.	Compacted +Tall Oil Pitch-A tarry semi-solid material which is a bi-product from pulping pine trees (SB)	0.055	33	5.45
4x	2006	2		Compacted +Bitumen Emulsion - A modified bitumen emulsion used as a hydrophobic biner for road bases (Eco)	0.055	33	5.09
Mt Barker[h] (16 plots)							
4x	2006	2		Control	0.05	33	8.13
4x	2006	2		Acrylic Polymer-soluble soil binder -Total Ground Cover (SL)	0.05	33	4.48
4x	2006	2	Loamy sand, clays and combination of clays and loamy sands.	Tall Oil Pitch-A tarry semi-solid material which is a bi-product from pulping pine trees. (SB)	0.05	33	6.06
4x	2006	2		Bitumen Emulsion - A modified bitumen emulsion used as a hydrophobic biner for road bases (ECO)	0.05	33	6.09
Frankland Vineyards [dc,d,f,g]							
Powerbark Ridge			Light Clay - 30% Surface Gravel			6	14
International Hill			Cracking Clay - 0% Gravel			15	5
Wilson's Pool	2004		Clay - 80% Surface Gravel	Compacted Earth and Acrylic Polymer (TGC)*		13	1.6
Great Southern	2004		Clay - 10% Surface Gravel	Compacted Earth and Acrylic Polymer (TGC)*		16	3.9
FRV			Clay - 40% Surface Gravel	Compacted Earth		4.5	5.3
Ferngrove (East)			Clay - 25% Surface Gravel			10	4*
Ferngrove (West)			Clay - 10% Surface Gravel			11	5*
Merredin RS[j]	2012			Permazyme (PK4) + cement	12		4.6

Data: a - PWD (1959); b - Laing (1981); c- Lanzke and Prince (2004); d - Lantzki and Stanton (2005); f- Short *et al.* (2006); g - Short and Lantzke (2006); h – BaekColes *et al.* (2011); i- Department of Agriculture of Western Ausralia (DAWA) (1980); J - Stanton per comm. Notes: *Antecedent conditions important ** These are the slopes if the main roads without batters. ***Experimental area formed into parallel 'roads' with road grader. Whole area sprayed with pre-emergence herbicide by mid April. Experimental treaments applied after 25mm rain. " Note this is 1 dry year record for 5 events ranging from 7-42 mm. ^low rainfall year. Improved in subsequent years. Figure given is an approximation. ~3 large rainfall-runoff events excluded due to ovetopping of the weir. Percentage respsonse is likley tto be high than that stated. Difference between trials in statitically difference (P <0.1).

RESULTS AND DISCUSSION

As agricultural operations and townships expanded in the dryland areas of the southwestern Australia, the need for water became increasing important. Prompting the initial research and observation on water harvesting by the Public Works Department (PWD) in the 1940s to 1960s. Observations suggested that rain falling on natural catchments does not runoff, either because it is absorbed into the soil or is evaporated. Initial methods of catchment improvements included burning surface litter and scrub and rolling the surface, met with limited success particularly with light rains (PWD, 1959). A grader and roller were then used on a slight slope to scrape the surface and compact the clayey soils or a "road" at Lake Grace (WA) in 1949-50 (Table 1).

This proved to be more successful in light rains at generating runoff. Thus, it was shown that bare sloping surfaces (provided the slope was of sufficient grade and did not encourage erosion) was more effective at generating runoff, even from light rains. Later work established that for example bitumen roads a rainfall-runoff threshold of +2mm was achievable (Laing, 1975. 1981; DAWA, 1980) – (Table 1), compared to farmland or natural catchment which requires at least 25mm (Coles *et al*., 2000; Coles *et al*., 2011; Stanton, 2005).

South-western Australia has exhibited both a warming and drying trend since the 1970's (see Figs. 3 and 4). As a result, this region has experienced substantial rainfall declines (up to 20% see Fig. 5) thereby reducing the effectiveness and efficiency of runoff generation from natural and untreated artificial catchments (Coles and Baek, 2012).

As rainfall declines and events suitable for generating runoff cease – there will be further reductions in the water available for agricultural production This understanding is critical to improving water supply security (or reliability) in a continuing drying climate that is affecting a larger proportion of the drylands and other industries e.g., Horticulture or Viticulture (Short and Lantzke, 2006; Baek and Coles, 2011. 2013a).

An analysis of rainfall records of two study sites at Mt Barker and Merredin, in the WA wheatbelt, demonstrates that not only has rainfall reduced in total (Fig. 6a) it has also shifted in terms of inter seasonal distribution (Fig. 6b). In the case of Mt Barker, a 30 year snapshot comparison of monthly rainfall totals between 1941-1970 and 1991-2020 shows statistically significant declines in rainfall of up to 30% in some months (Fig. 6a).

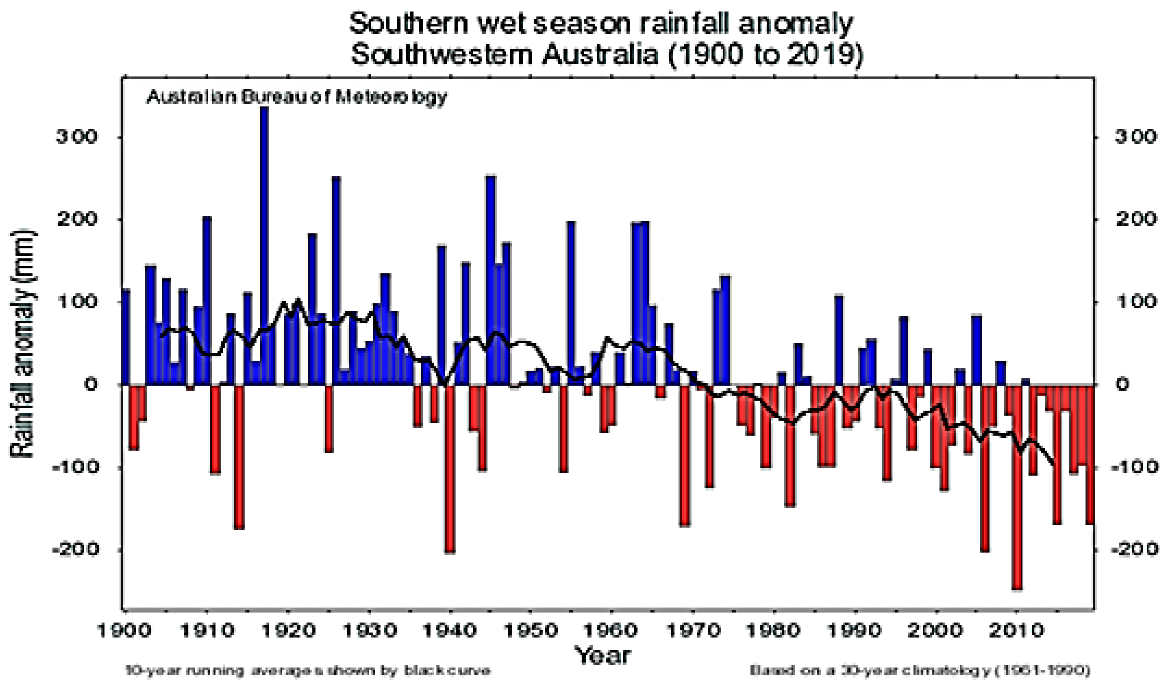


Fig. 3. Southern wet season anomaly with 10 year moving average for south-western Australia (1900-2019) depicting the continued decline in mean annual wet season rainfall since the 1970s. The reduction in rainfall is

not uniform, but there is known to be a non-liner correlation between a reduction in rainfall totals and runoff generation (Department of Primary Industries and Regional Development, 2020)

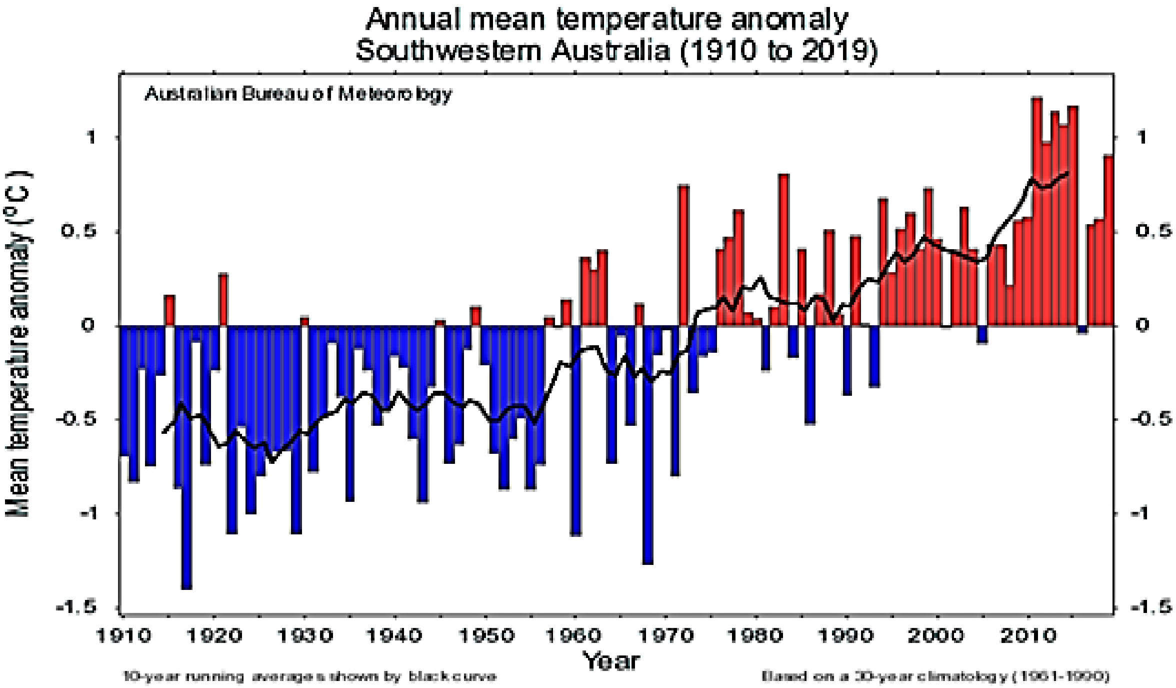


Fig. 4. Mean Annual temperature anomaly with 10 year moving average for southwestern Australia (1910-2019) showing a steady increase temperature over time particular since the mid 1970's (Department of Primary Industries and Regional Development, 2020)

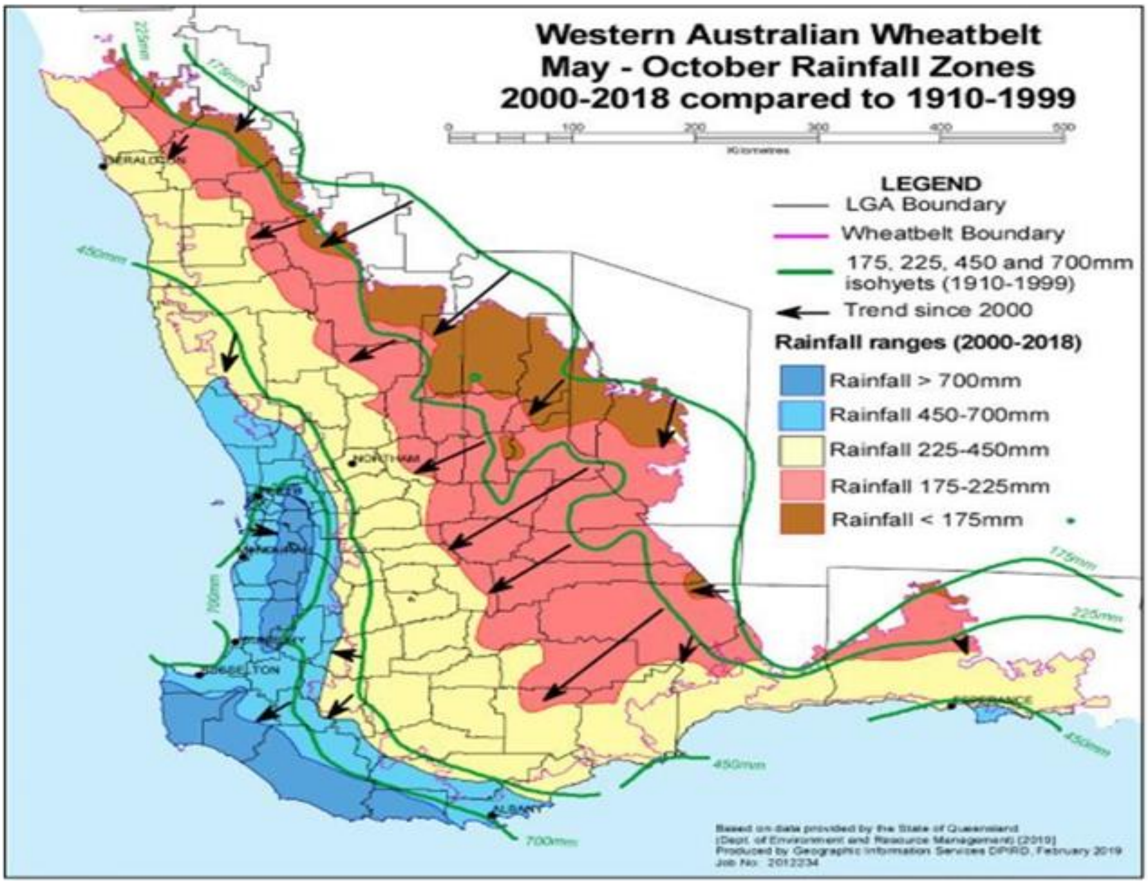
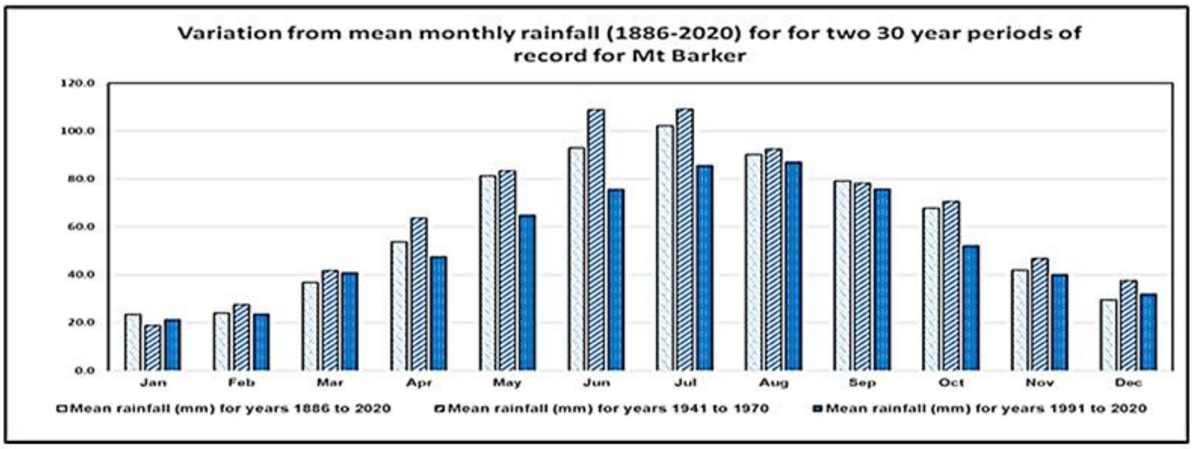


Fig. 5. Rainfall shifts in the May to October growing season period for south-west Western Australia. Illustrates the effect of the rainfall anomaly shown in Figure 2. Note that the decline in annual rainfall has a significant

impact on the amount of runoff generated during the year as streamflow (Department of Agriculture of Western Ausralia (DAWA), 1980)



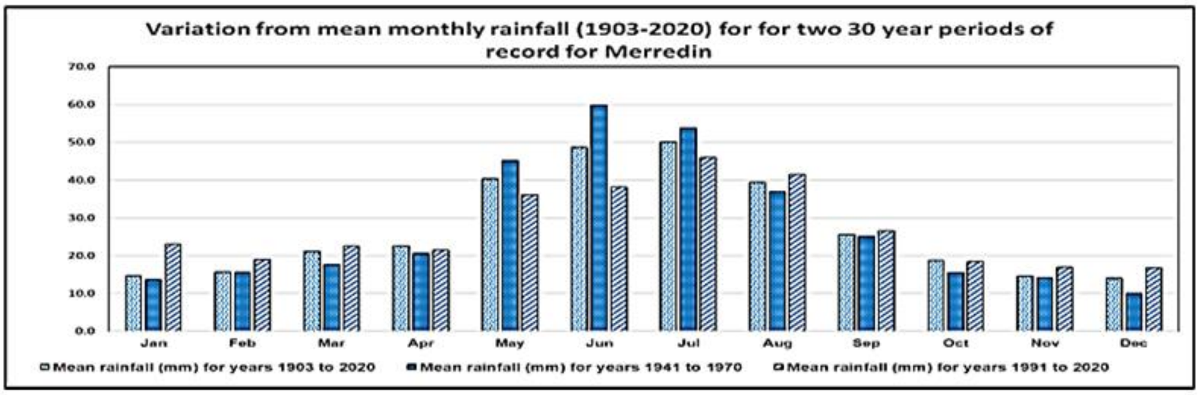


Fig. 6 (a, b). Showing impact of monthly rainfall variation at Merredin and Mt Barker since 1991 compared to the long term mean annual totals and the period between 1941-1970. Mean annual totals have remained similar at Merredin but demonstrate a phase shift since 1970 with more rain falling later in the growing season and in summer- with less falling in spring and winter. While Mt barker records show a significant decline over the spring-winter period (Apr-Jul). Note year 2020 is an incomplete record

Table 2. Demonstrates the rainfall runoff response from different rainfall classes for the Mt Barker experimental catchments treated with surface sealants

		Rainfall Class				
		<5	5 to 10	10 to 15	over 15	Total
Control	Total RO (mm)	7.71	17.64	16.57	6.79	48.71
	Average (Per Event)	0.09	0.77	1.51	2.26	
Polymer	Total RO (mm)	53.79	60.77	52.71	17.52	184.79
	Average (Per Event)	0.67	2.64	4.79	5.84	
Bitumen	Total RO (mm)	29.1	38.85	35.95	11.74	115.64
	Average (Per Event)	0.36	1.69	3.27	3.91	
Tall Oil	Total RO (mm)	31.23	36	34.14	9.59	110.96
	Average (Per Event)	0.39	1.56	3.10	3.19	

The same data snapshot for Merredin illustrates that rainfall has shifted inter-seasonally, with more rain now received in summer and autumn and less in spring and winter, which is critical for the growing season (Fig. 6b).

Furthermore, in response to declining rainfalls, DAWA[1] and the Wine Industry embarked on a series of laboratory and plot trials to identify the chemical treatments (Fig. 7) that may be utilized to ensure greater security of water supply to minimize losses due low rainfall years. While standard well-maintained and compacted roaded catchments have a runoff threshold of around 10-12mm it was expected based on earlier research (Laing 1975. 1981) that. chemically treated artificial catchments (even on sandy soils) would reduce this threshold to 4-8 mm or less, depending on treatment, site, and effective rainfall.

Soil sealants could then be used on previously unsuitable soils and were shown to be relatively cheap (Short and Lantzke, 2006) Using the results of this research to focus on specific treatments, further larger plot trials were conducted at Mt Barker and Merredin Research Stations (Table 1). With a more detailed analysis of the rainfall-runoff response given in Table 2. The analysis of the 2006-7 rainfall data collected during trials at Mt Barker highlighted the variation in response associated with rainfall classes (Table 2). With significant runoff generated from treated catchments for rainfall events <10 mm relative to the control catchment (Fig. 8).

The extended plot trials at the research stations highlighted that antecedent moisture conditions are still an important factor in reducing the runoff threshold even for enhanced catchments with very low thresholds (Baek and Coles, 2013b) supporting the observation made 50 years earlier by the Public Works Department (PWD, 1959).

Again, an important finding, as the rainfall records show that while rainfalls are in decline, the classes of rainfall are also shifting, with more rain delivered in <10mm and >25mm daily event totals. While those events normally expected to generate about 75% the runoff (before treatment) in the 10mm - 25mm range are in decline. For the treated catchment scenarios 58% of the runoff is generated from the <10mm threshold, with only 31% from the 10-25mm range. As a result catchments with higher runoff thresholds, nominally those that are untreated, will generate considerably less runoff and be less resilient in a drying climate with variable rainfall patterns.

[1] DAWA- the Department of Agriculture WA; also know as the Department of Food and Agriculture WA (DAFWA)

Product	Soil type	Incorporated or surface applied	Total ml/m^2 applied	Dilution rates	No. of coats
Soil-Loc (Total Ground Control)	Clay and loamy sand	Surface applied	40	50:1	1
Gluon	Clay and loamy sand	Surface applied	200	10:1	1
Claycrete II	Clay	Incorporated	30	Diluted to achieve OMC for compaction	1
PK4	Clay and loamy sand	Incorporated	3	Diluted to achieve OMC for compaction	1
Dustex	Clay and loamy sand	Incorporated	630 (440 g)	Diluted to achieve OMC for compaction	1
Soil Bond	Clay and loamy sand	Surface applied	450	10:1	4
Soil Bond	Clay and loamy sand	Incorporated	2000	1:1 + water to OMC	1
Ecotrax	loamy sand	Surface applied	100	10:1	2
Ecotrax	loamy sand	Incorporated	1000	1:2 to 1:5 to OMC	1

Fig. 7. Chemical treatments tested and trialed for ACRCSs by DAWA and Wine Industry at Mt barker and Franklands (Lantzke and Prince, 2004; Short and Lantzke, 2006)

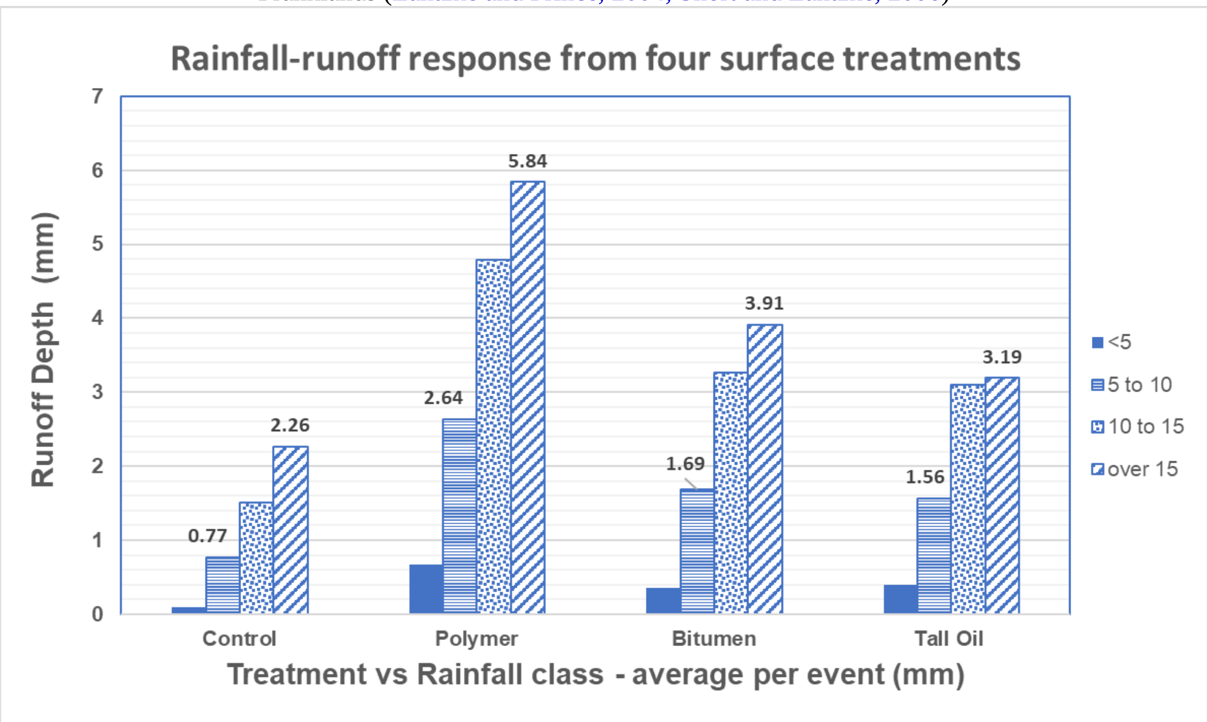


Fig. 8. Runoff generated per rainfall class from 117 rainfall events between Apr-2006 and Dec 2007. Note that ~ 58% of runoff is generated from events <10mm, and ~31% is generated from the critical >10-<25mm range.

Water security remains a significant issue for dryland farmers in southwestern Australia. Continuous improvements in water harvesting using ACRCSs, and surface treatments has highlighted the need to provide additional investment in surface sealants and treatments to reduce the runoff harvesting thresholds. The data presented here has shown that dam-catchment system constructed two decades (or more) ago are now becoming less efficient as shifts in rainfall patterns reduce their harvesting efficiency exposing more farmers to the potential impacts of drought and lost the productivity.

This has been borne out by the need for the WA State government to invest more than A$6.38M in water deficiency support for farmers and rural communities during 2017-20, 53% of which was for carting water (Smith, 2020).

CONCLUSION

This review has highlighted the processes and treatments required to increase the potential water harvested from different landscapes in semi-arid areas. Initially natural catchments were used, then as demand increased, artificial catchments – scarped and rolled - were deployed in the 1940-1960s. Later as the southwestern region faced expanded agricultural demand and a drying climate, roaded and compacted artificial catchments were introduced, further reducing the runoff threshold from 25mm, to around 10-12mm.

Furthermore, in the 2000's as other industries such as the Wine Industry experienced lower rainfalls, higher value crops promoted the idea of using other methods such as chemically applied soil sealants- where the additional cost were justified by the expected returns. Threshold for 4-8mm could be achieved, and potentially <2mm for bituminized catchments (Table 1). This is particularly important in areas where space may be limited such as the grape growing and horticulture industries.

Furthermore, by lowering the runoff threshold and improving the efficiency of roaded catchments, the volumes of water delivered to dams could be maintained or even enhanced, increasing the reliability of ACRCs and water supplies, allowing agricultural production systems adapt to the drying climates. In providing greater resilience to climate change, water security, water and farm productivity can be sustained.

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