COOPERATIVE RESEARCH CENTRE FOR **CATCHMENT HYDROLOGY**

WATER FARMS: A REVIEW OF THE PHYSICAL ASPECTS OF WATER HARVESTING AND RUNOFF ENHANCEMENT IN RURAL LANDSCAPES

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Laura Richardson / Peter Hairsine / Timothy Ellis

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Water Farms: A Review of the Physical Aspects of Water Harvesting and Runoff Enhancement in Rural Landscapes

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Preface

It is common to accept that the amount of water our streams receive cannot be changed. Though it is subject to the variation of climate and climate change, there is little discussion of what can be done to manage the input of quantity to our streams. In contrast, there is an extraordinary amount of discussion, regulation and action concerning the storage and distribution of streamflow.

Water farming is an approach to the problem of managing the quantity of water input to our streams, and is an idea that has been around for thousands of years. In this concept, land managers are able to generate more runoff for a given amount of rain than would happen in normal circumstances. Historically, most examples focused on providing extra water from a farm for use on the same farm. However, there are considerable prospects for "water farms" - enterprises that use water harvesting techniques to provide additional water into the river system and new water markets. It is these prospects that have prompted this review.

Overall, this report finds that i) water farms are technically feasible, ii) analysis of their cost effectiveness in providing additional water for specific uses is required, iii) there are likely to be regulatory barriers to the adoption of water farming for enhancing off-farm water security and iv) further investigation in the use of water farms to enhance the availability of water is warranted by Australian water managers.

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Abstract

The term ‘water farming’ refers to a group of techniques for increasing runoff that have been developed and improved by land managers over many centuries. Water farming, as defined here, is a subset of water harvesting, which describes all techniques of runoff collection. Most of the documented examples of water farming involve the enhancement of runoff from a soil to provide additional water for plants or a storage that is a few metres downslope. As the flow of many of the rivers of the world has been put under stress through very high levels of water allocation, water harvesting may have a new role in providing additional inflow to streams that can be part of the water budget or market. The increased value of water that has resulted from the creation of water markets may make water harvesting a feasible activity at a catchment scale.

In this report we review the historical examples of water harvesting. We list and compare the surface treatments, size, and layout of such systems and give details of their performance, costs and durability. We find that there are several viable systems of water harvesting that have been extensively trialed in a range of environments. Limitations on the use of these systems are described. The variety of surface treatments includes the use of wax, compacted earth, salt and gravel covered membranes.

There is sufficient experience (e.g. Pacey and Cullis, 1986) in water harvesting that it should be considered as a potential mechanism for providing additional water for streams that are under stress, and future steps should include evaluation of the economics of “Water Farms”. It is likely that there are institutional barriers to enterprises selling enhanced runoff from a land unit for particular jurisdictions. There are, therefore, still several steps to be in place before large-scale water farms, focussed on providing additional streamflow, become a reality.

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1. Introduction

Water harvesting is the process of collecting runoff from rainfall or snow from a natural or artificial catchment surface. Natural surfaces such as desert pavement and rock outcrops can be used to collect water; however, runoff is not substantial unless rainfall is intense enough to overcome natural infiltration rates (Frasier and Myers, 1983). For thousands of years humans have been modifying or treating catchment surfaces to increase surface runoff. Researchers in Israel's Negev Desert have reconstructed water harvesting systems that date back 4,000 years. It was found that farmers cleared hillsides of rocks to smooth the soil and increase runoff, allowing grain crops to be grown in areas with an average annual rainfall of 10 mm (Myers, 1967). Seven hundred to nine hundred years ago, American Indians used similar systems in the southwestern United States (Myers, 1975).

Methods to increase surface runoff range from simple treatments, such as clearing, smoothing and compacting the soil, to expensive or complex ground covers such as sheet metal or asphalt-fibreglass membranes. The runoff from a treated catchment area can be used immediately by crops and stored in the root zone, or it can be collected and held in storage tanks for future use (Frasier and Myers, 1983).

Studies of artificial catchment surfaces began in the 1950s when artificial rubber and vinyl or polyethylene membranes were trialled in the United States. Many of these systems failed within 5-10 years because of wind damage and solar radiation. Studies to develop and evaluate new methods and materials for constructing water harvesting systems began in the 1960s in the United States and other arid and semi-arid countries. Researchers were looking for cheaper and more reliable catchment treatments, and focus moved from groundcovers to using the soil itself as a catchment surface (Frasier and Myers, 1983). The literature reviewed for this report is dominated by examples from the United States in the 1970s and 80s. It was found that very little material on this topic has been written since this time.

In many dry areas where rainfall is low and erratic in distribution, water harvesting supports thriving agricultural production (Oweis, 1999). In Australia, there is potential for water harvesting in agricultural areas and in semi-arid regions. Both irrigation and dryland farming would benefit from water harvesting by using the collected runoff for stock watering and irrigating crops. Water harvesting could provide more water for users and reduce the amount of water extracted from rivers. In drought years, water farming could provide significant contributions to inflows to rivers and allow more water to be allocated for environmental purposes.

There is also potential to set up “water farming”. This concept consists of harvesting water from a catchment surface and selling the water to other users, thereby having an economically viable income. Areas that have been degraded or are unsuitable for growing crops could be used to harvest water, returning value to the land.

Currently in Australia there are many examples of water harvesting and few of water farming. The reason for this is unclear, but institutional issues may contribute. Much water resources legislation and regulation is based on the principle that the Crown owns the rainfall and runoff. This may serve as a disincentive for the development of water farms where additional runoff is sold off-farm. This issue is beyond the scope of this report but warrants further analysis.

2. Styles of Water Farms

There are two main types of water harvesting systems. The first type of system consists of a catchment area and a cropping area. In this system, water runs off the treated catchment surface and into the cropping area, which increases the water yield to the crop and improves productivity. The second type of system consists of a catchment area only and runoff water is collected and stored. This water can then be used or sold when needed.

Both types of water harvesting system are found on varying spatial scales ranging from 10 m^2 catchment aprons to regional water farms with hectares of land collecting runoff, and each type is not restricted to any one method of surface treatment. The treatment chosen for a particular system depends on the individual design and objectives of the system, and must also take into account the regional weather conditions such as the amount and variability of rainfall.

2.1 Catchment-Crop Systems

Microcatchment and mini-catchment water harvesting systems are small catchments that have a runoff area and a basin area where a tree, bush or row of crops is grown (Boers, 1994). These systems are designed on the basis that the smaller the catchment surface the greater the runoff efficiency, as runoff increases with increasing slope and decreasing slope length (Li *et al.*, 2001). Therefore catchment-crop systems are usually in the order of a few hundred square metres with a maximum flow distance of 100 m. In these systems, runoff comes directly off the catchment surface and into the cropping area, where it is allowed to infiltrate into the soil and be stored in the root zone (Boers, 1994).

Microcatchments are the smallest scale water harvesting systems and provide the highest runoff percentage per unit of watershed area (Dutt, 1981). They can range from 10 to 1000 m^2, with the size and design of the catchment dependent on plant requirements and local precipitation (Li and Gong, 2002). Their design consists of a catchment area surrounding a tree or bush, and runoff is directed to the centre where the plant is growing. The area immediately surrounding the plant has a higher amount of infiltration and more water is available to the plant (Oron and Enthoven, 1987). Figure 1 shows one design of a microcatchment, with a catchment apron (CA) and an infiltration basin (IB).

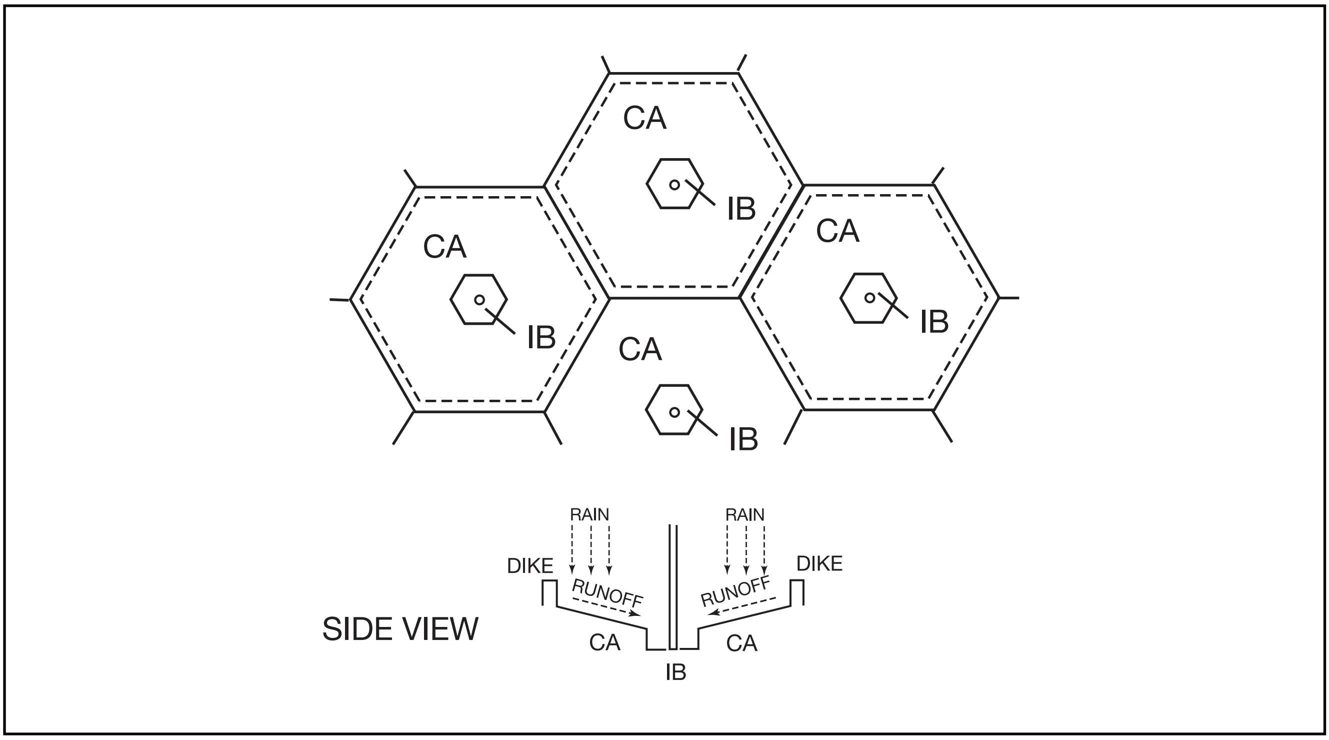

Figure 1. A Schematic Description of a Microcatchment Layout Consisting of Regular Hexagons. (Source: Oron and Enthoven, 1987)

Mini-catchment or strip runoff farming systems consist of a catchment area adjacent to a row of crops. Compared to microcatchments, these systems can be effective on larger scales because the size of the catchment area is not dependent on spacing between individual plants in the crop. However, these systems are also restricted by slope length to maintain maximum runoff efficiencies. In a farm setting, a number of catchment aprons can be set up between rows of crops, and multiple systems can potentially cover hectares of land. Figure 2 shows two systems together (Oweis *et al.,* 1999).

The catchment surface can be treated in a number of ways to increase the amount of runoff. Li and Gong (2002) however, studying microcatchment systems in China, stated that for economically viable crop production, only the cheapest method of clearing vegetation and smoothing and compacting the surface could probably be used (Cluff and Frobel, 1978; cited in Li and Gong, 2002).

There are various catchment to crop ratios that give different water efficiencies and production rates. The system can be adjusted to suit the topography or layout of the farm and to meet the needs of the farmer. In an experiment with blue panicgrass, different catchment to crop ratios were tested to determine the most productive design of a system. It was found that highest yields were achieved with a catchment crop ratio of 2:1 using a wax surface treatment, and 3:1 for bare soil and grass catchment surfaces. Table 1 shows yields of blue panicgrass for different catchment to crop ratios (Frasier and Schreiber, 1978).

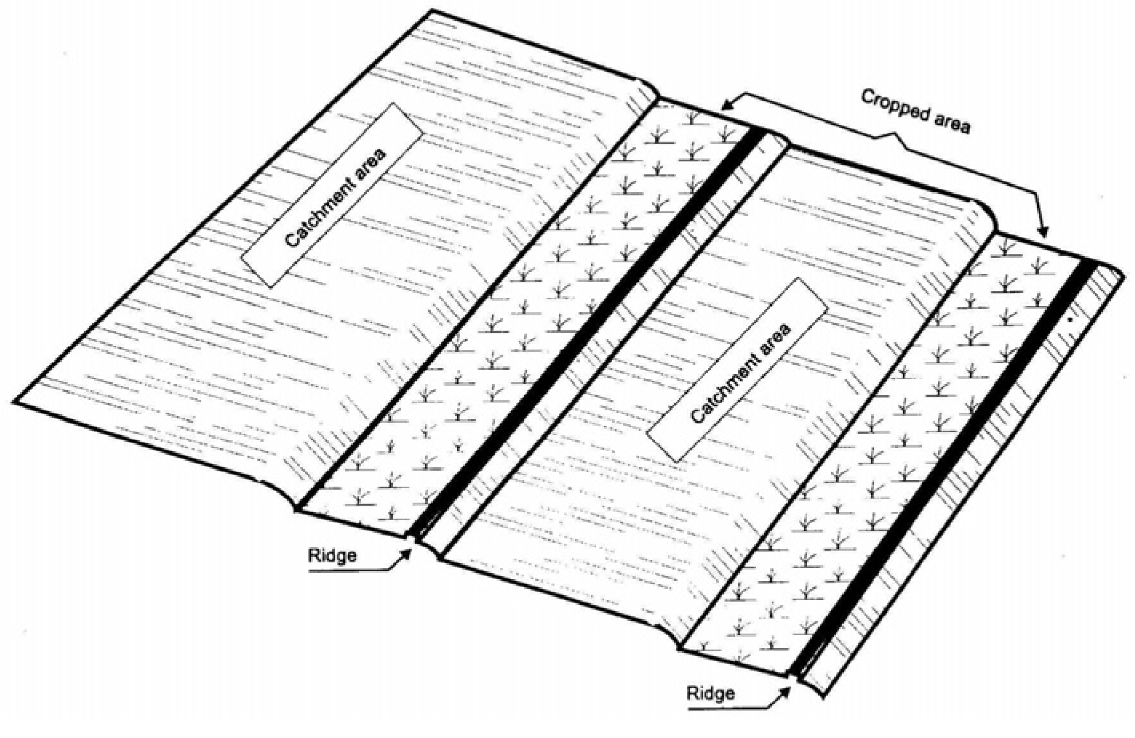

Figure 2. Mini-Catchment (strip) Runoff Farming Water Harvesting. (Source: Oweis *et al.*, 1999)

2.2 Catchment-Only Systems

The objectives of a catchment-only water harvesting system are to collect and store water to be used off-farm. These systems consist of a catchment surface with drainage channels to collect water, and a storage tank to hold the water until it is needed. Slope lengths can be minimised by constructing the drainage channels between catchment surfaces to collect and direct water to the storage tanks (Laing, 1981). Because of this, there is potential for these systems to be constructed on scales of hundreds of hectares, although no literature was found on scales such as this.

Table 1. Blue Panicgrass Yields (Kg/Ha) From The Montijo Flat Forage Plots. (Source: Frasier and Schreiber, 1978)

Harvest Date	Area Ratio Catchment:Crop	Yield (kg/ha)		
		Catchment Area Treatment		
		Wax Treatment	Bare Soil	Grass
Aug 1974	0:1	961	961	961
	1:1	1909	1246	1068
	2:1	1932	1755	1203
	3:1	1136	2338	1093
Dec 1975	0:1	186d†	186d	186d
	1:1	1333bc	536d	433d
	2:1	2920a	683cd	421d
	3:1	1939b	949b	494d
Aug 1976	0:1	227e	227e	227e
	1:1	1543c	986cde	583de
	2:1	2993a	1616c	951cde
	3:1	2602a	2211b	1308cd
Feb 1977	0:1	21	21	21
	1:1	284	218	60
	2:1	300	360	190
	3:1	326	720	181
Oct 1977	0:1	303	303	-
	1:1	2274	1542	-
	2:1	2124	1564	-
	3:1	1824	3178	-
Total 1974-1977	0:1	1698	1698	1395††
	1:1	7343	4528	2144
	2:1	10269	5978	2765
	3:1	7827	9396	3076

† Duncan multiple range test (P=0.05) for yields from crop growing area. Means within a year followed by no letters in common are significantly different (Schreiber and Frasier, 1977; cited in Frasier and Schreiber, 1978).

†† For the period of Aug 1974 – Feb 1977. Grass plots removed after Feb 1977.

These systems can be useful in dry regions or during droughts when water is a scarce resource. Water can be sold to agriculturalists, graziers or councils for town water supplies, and there is potential for it to be added to rivers to maintain environmental flows.

An example of a catchment-only system is a 'roaded catchment'. This catchment consists of a surface of compacted soil with parallel ridges or roadways at a gradient that allows runoff to occur without causing erosion of the channels (Figure 3) (Laing, 1981). In Western Australia, the Public Works Department has been using roaded catchments since the 1950s for town water supplies and to fill farm water tanks. In 1973, there were around 2,500 roaded catchments on farms in Western Australia (Burdass, 1975).

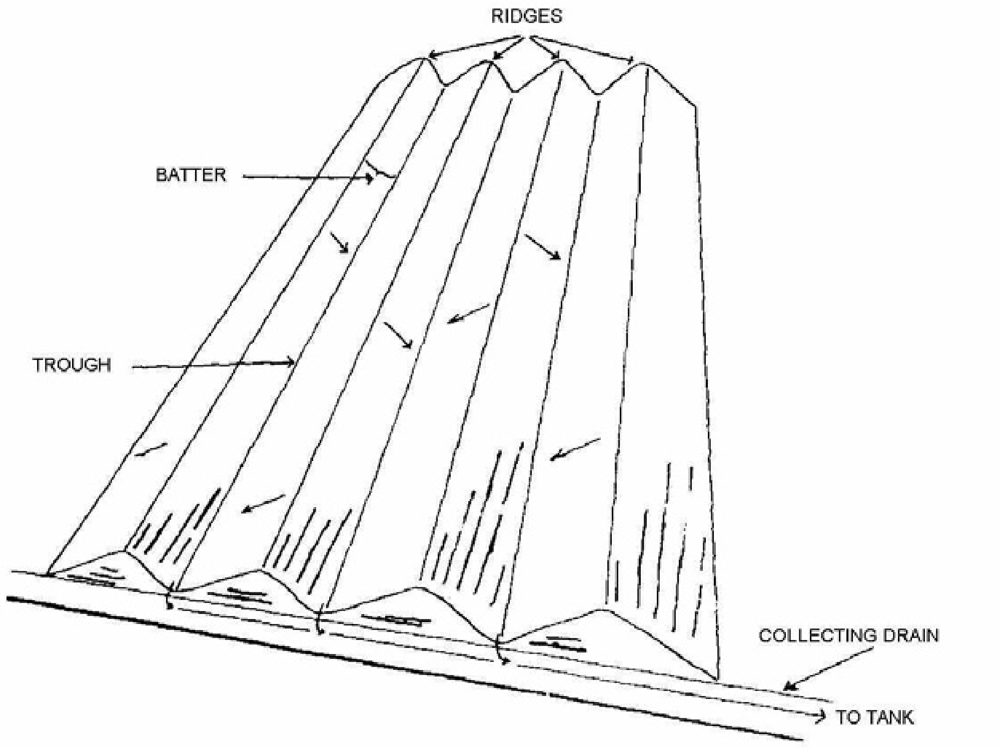

Figure 3. The Design of a Roaded Catchment. (Source: Burdass, 1975)

3. Surface Treatments

This section summarises the different methods used in water harvesting systems to increase surface runoff. Methods described in the literature include mechanical treatments, applications that create hydrophobic surfaces or deteriorate the soil structure to create impermeable layers, and materials that cover the surface.

For each runoff, enhancement method comments are made on the biophysical constraints to the environments where this type of water harvesting system has been trialed, the runoff efficiency of the trialed system, factors affecting the durability of the system, costs associated with the establishment and operation, and finally any recorded comments on the water quality of runoff from the system.

Myers (1961; cited in Myers, 1975) listed some of the desirable characteristics of surface treatment materials as follows:

1. Runoff from the structure must be non-toxic to man and animals.
2. The surface of the treatment should be smooth and impermeable to water.
3. The treatment should have high resistance to weathering damage and should not deteriorate because of internal chemical or physical processes such as crystallisation.
4. The structure need not have great mechanical strength, but should be able to resist damage by hail or intense rainfall, wind, occasional animal traffic, moderate flow of water, plant growth, insects, birds and burrowing animals.
5. The material used should be inexpensive on an annual cost basis and should permit minimum site preparation and construction costs.
6. Maintenance procedures should be simple and inexpensive.

3.1 Overview of Performance

3.1.1 Biophysical Constraints

Water harvesting systems are most efficient when they are specifically designed to suit local variations in topography, soils, climate and hydrology, and a site is often selected based on these factors. It is advantageous to select a site where the catchment can make use of natural surface topography as it reduces the amount of site preparation. Designing a water harvesting system with a flexible catchment shape allows the natural surface topography to be utilised (Frasier and Myers, 1983).

A number of surface treatments require specific soil types and slope angles for them to work effectively for as long as possible. Premature treatment failure can occur if the treatment is installed on the wrong type of soil or on slopes that are too steep. The catchment slope should only be steep enough to cause runoff and treatments that have problems with erosion should be used on slopes of less than 5% (Frasier and Myers, 1983).

Climate is a very important factor because the surface treatment needs to withstand annual variations in temperature, wind, solar radiation and the nature of precipitation. Some surface treatments are susceptible to wind damage and UV radiation, and hydrological factors, such as rainfall variability, the nature of storms and the location of rain-shadow areas, also need to be considered when choosing a water harvesting site (Mickelson, 1975).

Site preparation includes clearing, smoothing and compacting the soil surface and applying a soil sterilant to prevent any unwanted plant growth. No details of the types of soil sterilants used were given in the literature reviewed here. There is no standard shape for a catchment, although square and rectangular shaped areas are commonly used with some treatments to minimise wastage of material. However, some materials, such as paraffin wax, can be easily applied on irregularly shaped catchments and can utilise natural surface topography (Frasier and Myers, 1983).

3.1.2 Runoff Efficiency

Runoff efficiency is defined as the percentage of rainfall that becomes runoff in the period that the trial site was monitored. This measure varies between 0% for systems where all rainfall is lost to 100% for ideal systems. Untreated soil surfaces typically have a runoff efficiency ranging between 0 and 40%, depending on the intensity of the rainfall event (Frasier, 1975b; Fink *et al.,* 1973). Losses in treated systems are associated with soil infiltration, depression storage and evaporation between rainfall and the measurement of runoff.

Runoff volumes for streams and water allocation are normally given in the units of millions of litres or megalitres (Ml). One megalitre is the equivalent of 100 millimetres of runoff from a hectare of land surface. Thus a runoff efficiency of 80% would provide 0.8 megalitres of runoff for a one-hectare catchment area subject to 100 millimetres of rainfall.

3.1.3 Costs of Treatments

The costs for different treatments outlined in this section generally only include the initial costs of the surface treatment and not additional costs needed to completely install a water harvesting system. Additional costs, such as site preparation, labour, piping, fencing, maintenance and installation of storage tanks, have not been included in many of these figures. Initial installation costs include the raw materials needed to seal or cover the catchment surface and, in most cases, the costs related to installation of these materials.

A large portion of the literature on this topic was written in the 1970s and 80s and prices cited in this section have not been converted to today's prices. However, all figures are labelled with the year that they were calculated.

3.1.4 Water Quality and Environmental Issues

The water quality of runoff from a water harvesting system is generally very good. Myers (1975) states that water quality is not a problem if the water is being used on crops or for livestock watering. However, water quality is an important issue when the water is being used for human consumption and additional filtration or treatment is generally needed.

For all treatments summarised in this section, with the exception of asphalt-fibreglass membranes, the treatment itself does not contaminate runoff water. However, erosion and animal traffic on the surface can pollute the water with sediment or faecal remains. In asphalt-fibreglass catchments, the membranes can oxidise and runoff water is often discoloured. It is thought to be harmless to humans but before this is proven it is not recommended for domestic use (Myers, 1975).

The literature did not cover any long-term environmental effects caused by these systems. It is a conclusion of this report that research is needed to ascertain whether there are any lasting environmental effects from the surface treatments. Furthermore, it is assumed that the salt-treatment would cause long-term damage, as the treatment works by breaking down clay aggregates and destroying the soil structure. However, it is thought that the other treatments are all reversible and any environmental effects would be removed once the treatment was discontinued. Before installing a water harvesting system it would be advisable to find out more about environmental impacts of the system you wish to install.

3.2 Compacted Earth Catchments

A cleared, smooth soil surface is one of the cheapest and simplest water harvesting methods. However, runoff efficiency is not very high compared to other catchment surface treatments and erosion can be a problem. The treatment consists of grading, smoothing and compacting the soil surface to induce runoff (Frasier, 1981).

Roaded catchments in Western Australia are compacted earth catchments that are commonly used for livestock watering and rural town water supplies. The catchment surface is cleared of vegetation, smoothed and compacted to reduce depression storage and infiltration, increasing the amount of runoff (Laing, 1981).

3.2.1 Biophysical Constraints

Laing (1981) concluded that this type of harvesting system could only be established on specific soil types and land surface gradients to maximise runoff and minimise soil erosion. Soils with clay contents greater than 25% are the most effective on bare soil catchments. Coarser soil types do not compact as well and do not produce significant surface runoff. Many of the soils used in constructing roaded catchments in WA are duplex soils with coarser material on the surface and clays below. Inverting this soil profile allows the clays to cover the catchment surface, and with compaction the runoff can be much higher than a natural catchment (Laing, 1981).

Because there is no soil stabilisation involved, care must be taken in designing the slope angles, catchment lengths and surface uniformity to minimise soil erosion (Firth, 1975; Hollick, 1975). Slope angles should be no more than 5% to minimise erosion and catchments should be engineered to limit hillslope lengths to about 100 metres (Frasier and Myers, 1983). This minimises the formation of rills and other erosion features and prolongs the life of the catchment surface.

3.2.2 Runoff Efficiency

Runoff efficiencies for this type of water harvesting catchment vary depending on the soil type and the amount of surface preparation. Cluff (1975) found that compacted earth catchments could yield runoff efficiencies of 30-60%. A four-year study of a roaded catchment at Newdegate in WA found that the average runoff was 33% of the annual rainfall. In the lowest rainfall year where only 295 millimetres (mm) fell, the runoff was 24% (Laing, 1981). Roaded catchments usually produce runoff from rains exceeding 8 mm, whereas storms must usually exceed 19 mm to produce runoff in natural catchments (Myers, 1967).

3.2.3 Durability/Maintenance/Lifespan

These catchments deteriorate over time because of surface weathering and erosion, growth of vegetation and trampling of livestock on the catchment surface. Yearly maintenance is needed for the removal of weeds, to repair areas damaged by erosion and to keep steady gradients. It is advisable to fence off the area to keep larger animals out so that the surface does not get damaged and the runoff water is not tainted (Burdass, 1975; Frasier, 1981). According to Cluff (1975) these catchments can last indefinitely. However, Frasier (1975b) predicted a life span of 5-10 years before recompaction or other major maintenance is needed.

3.2.4 Costs

Laing (1981) found that when comparing all the different water harvesting techniques, bare compacted soil and roaded catchments are the cheapest. In WA, the catchments are primarily used by commercial farmers and need to be economically attractive (Laing, 1981). The cost would be dependent on site accessibility, soil type, type of terrain and natural vegetation coverage. Costs would be less per acre when constructing a larger catchment compared to a smaller one and constructing several catchments at one time would also reduce costs (Cluff, 1975).

In the US, the total cost of a one-acre catchment was approximately US$300 including equipment rental and labour, based on 1974 prices (Cluff, 1975). For a roaded catchment in WA, the average total cost would be around A$500/ha, based on 1980 prices (Laing, 1981).

3.2.5 Water Quality

Cluff (1975) found that runoff from these catchments can have a considerable amount of sediment. If it is being used for domestic purposes, the water needs to be treated or filtered as necessary.

3.3 Salt-treated Soil

Catchments can be treated with sodium salt to reduce infiltration and increase runoff. Sodium, in the form of chloride or carbonate, promotes breakdown of the soil aggregates and disperses the clay. This causes clogging of the soil pores which forms an impermeable layer (Frasier and Myers, 1983). This type of treatment is simple to design and only needs simple hand tools and commonly used farm machinery to construct (Dutt, 1981). The source of the salt was not specified in these papers.

There is some potential for this type of harvesting to occur on salinised land, although no references describing this type of operation have been found. In Australia, there are areas of agricultural land that have been salinised and have lost their potential to grow crops. By converting these areas into water harvesting catchments, the land can reclaim its economic value by harvesting and selling water.

3.3.1 Biophysical Constraints

To prepare the catchment, the surface needs to be cleared of vegetation and smoothed. The salt can be applied directly to the surface as a dry material or water solution, or it can be mixed into the top 5-10 cm of soil. Once the salt has been applied, the soil is then compacted after a rainfall event or another form of wetting so that a maximum soil-salt density in the surface layers is achieved (Frasier and Myers, 1983).

Because of the importance of clay in the effectiveness of the treatment, the soil needs to have a clay aggregate component of at least 15% by weight (Frasier *et al.,* 1987). In relation to topography, the salt treatment does not stabilise the soil, therefore slopes should only be around 2-4% to maximise runoff with a minimal amount of erosion (Dutt and McCreary, 1975). Frasier *et al.,* (1987) found that soil erosion is not a problem on soils that develop a gravel layer.

3.3.2 Runoff Efficiency

Runoff efficiency depends on the soil type and the characteristics of the rainfall. Average runoff values usually range from 40-75% (Cluff, 1975). On suitable soils with high intensity rains, runoff can be up to 89% (Frasier *et al.,* 1987). Hillel (1965; cited in Myers, 1967) found that treating cleared and smoothed sandy loam and clay loam soils with $NaCO_3$ increased annual rainfall runoff to 70%.

3.3.3 Durability/Maintenance/Lifespan

Cluff (1975) stated that the estimated life of the treatment is indefinite with proper maintenance. This maintenance would include weed removal, recompaction and additions of sodium salt when necessary. A study of field-sized water harvesting plots treated with sodium carbonate solution showed that an increase in runoff efficiency was sustained for three years but after that time the treatment was no longer effective (Frasier *et al.,* 1987). Therefore, applying additional salt after 3-5 years would be needed (Frasier, 1975b). It was also reported that there was an apparent downward migration of the dispersed clay lenses over time (Cluff *et al.,* 1972; cited in Frasier *et al.,* 1987).

3.3.4 Costs

Installation costs depend on the site conditions and available labour and equipment, and can therefore be highly variable. Frasier *et al.,* (1987) estimated the total installation cost, based on 1984 prices of a salt-treated catchment, to be US$2,500-7,000/ha, with annual maintenance costs estimated at US$300-2,200/ha. In a 500 mm rainfall zone, the water costs from this type of catchment were estimated at US$0.08-0.59/1,000L.

3.3.5 Water Quality

In a study using sprinklers to simulate rainfall, runoff water from two salt-treated plots was analysed for water quality. With the exception of sodium, the runoff water quality was not affected by the salt treatment. Sodium was slightly higher in runoff water from the test plots compared to that of the untreated plot (Table 2) (Frasier *et al.,* 1987).

Erosion from this type of treatment is common and the runoff water can have high amounts of sediment. Hillel (1967; cited in Frasier *et al.,* 1987) concluded that plots treated with sodium salt alone had a serious problem with soil erosion and that some form of soil stabilisation was needed. In some arid areas, however, a natural gravel 'desert' pavement can form on the surface, stabilising the soil and reducing erosion (Frasier *et al.,* 1987).

3.3.6 Working Examples

Agricultural crops have been grown using water from salt-treated water harvesting systems in several areas (Dutt, 1981; Dutt and McCreary, 1975; Fink and Ehrler, 1981). Grapes and certain fruit trees have been produced on study catchments monitored by the University of Arizona in the southwest United States. The catchments have produced wines of good quality with yields comparable to those from untreated, irrigated plots. Deciduous fruit trees, such as peaches and apricots, were adaptable to production on salt-treated catchments, although apple and pear cultivation failed due primarily to other factors, such as a lack of sufficient chilling of the trees to favour fruit growth (Mielke and Dutt, 1981).

3.4 Paraffin and Other Wax Sealants

By applying paraffin wax to the soil a water repellent surface can be obtained. The wax coats the soil particles and creates a layer that resists infiltration and increases runoff. The wax does not plug or clog soil pores (Frasier, 1980). Residual waxes have also been tested for use in runoff farming and are more adhesive, less costly and less brittle than paraffin. However, the physical and chemical properties are generally more variable and unpredictable and more research is needed to make these waxes more applicable (Fink, 1982).

The treatment consists of applying wax with a low melting point onto a prepared catchment surface in either melted form or as wax flakes. With successive warm days, the wax remelts and penetrates into the top 1-2 cm of soil, coating the soil particles with a thin wax film that is water repellent. Each time the wax is remelted by the sun it goes deeper into the soil, creating a thicker impermeable layer (Frasier and Myers, 1983). Frasier (1980) records that the paraffin wax treatment has been used successfully on catchment areas up to 0.33 ha.

3.4.1 Biophysical Constraints

The wax treatment is most effective in climates that have temperatures exceeding that of the melting point of the wax during some part of the year, so that the wax

Table 2. Mean and 90% Confidence Interval of Runoff Water Chemical and Electrolytic Analysis from Sprinkler Tests with Tap and Distilled Water on Page Ranch Runoff Farming Site. (Source: Frasier *et al.,* 1987)

	Type of Spray Water		Test Location					
			Salt-1		Salt-2		Untreated	
	Tap	Distilled	Tap	Distilled	Tap	Distilled	Tap	Distilled
Sodium	37	1	55±4	15±4	61±12	22±16	42±2	10±6
Potassium	2	<1	3±2	1±2	5±2	1±2	8±8	3±2
Calcium	36	2	34±4	2±2	34±4	4±6	37±4	2±2
Magnesium	11	<1	11±2	1±2	12±2	2±2	11±2	2±2
Electrical Conductivity	0.48	0.02	0.54±0.04	0.09±0.04	0.60±0.02	0.11±0.02	0.51±0.04	0.07±0.02

can remelt and readjust to surface changes. For the establishment of this system the catchment surface needs to be smoothed and compacted and reasonably free of gravel and small rocks. The treatment has been particularly applicable to lighter, coarser textured soils with less than 20% clay, such as sandy and sandy loam, but has not been successful on soils with expanding clays or in areas where freeze-thaw cycling is common. The treatment works well on slopes between 3-5% (Frasier and Myers, 1983) but soil erosion has been a problem on slopes exceeding 5% with lengths greater than 30 metres (Frasier, 1980).

3.4.2 Runoff Efficiency

The wax treatment has excellent runoff efficiency on suitable soils. Runoff is 80-95% with rainfalls of 2.5 mm or more (Frasier *et al.,* 1979). During cold winter periods the wax can harden and crystallise, reducing runoff by 10-15% (Frasier and Myers, 1983).

At the University of Arizona's Granite Reef test site, paraffin wax catchments were still operational after seven years, with runoff efficiencies averaging 87%. The average for the seventh year was 85%, only 2% less than the seven-year average (Fink *et al.,* 1980).

In a study where a number of different water harvesting techniques were tested, it was found that the smallest decrease in runoff efficiency and increase in threshold values with time occurred with the wax-treated system (Figure 1) (Emmerich *et al.,* 1987).

3.4.3 Durability/Maintenance/Lifespan

The wax is relatively resistant to sunlight deterioration, but needs to be fenced off to protect the surface from large animals. Before application of the wax treatment the soil should be sterilised to stop plant growth, and through the life of the treatment the catchment should be checked regularly for weeds (Frasier and Myers, 1983). It is also important to apply the necessary amount of wax to the soil surface, as some catchments have failed from a low application rate of wax (Fink *et al.,* 1980).

Because the wax moves further into the soil with each remelting by the sun, eventually the surface will not be adequately covered and a gradual loss of water repellency on the soil surface will occur. Therefore, small reapplications of wax where needed should maintain high runoff efficiencies

Also, the wax provides some soil stability for 6-12 months, but movement into the soil profile will reduce the wax's stabilising effect on the surface and erosion and removal of the wax can occur (Frasier, 1981).

The projected life before major retreatment is required is 5-10 years (Frasier and Myers, 1983). Catchments constructed at the University of Arizona's Granite Reef test site had received no maintenance after seven years, except for the removal of weeds at plot edges, and had still retained high runoff efficiencies (Fink *et al.,* 1980).

3.4.4 Costs

The initial costs of the treatment are relatively low for the high amount of runoff produced. Estimated costs (in 1981 prices) for materials are US$6,000 to $12,000/ha. The typical installation time for a 0.1 ha catchment is six hours (Frasier and Myers, 1983).

Two wax treated catchments installed in northwest Arizona provided water at costs of US$4.15 and US$3.90/1,000 L (1974 prices). The total installation costs for the two catchments averaged US$9,000, with one catchment 0.4 ha in size and the other 0.3 ha. This included surface treatment, installation of a storage tank and other costs, such as piping and fencing (Cooley *et al.,* 1978).

3.4.5 Water Quality

The water quality from a wax treated catchment is excellent. Fink *et al.,* (1973) found that organic matter and salt content was low and percentage light transmission of the runoff water averaged greater than 90%. As paraffin waxes are approved for human consumption, contamination of the runoff water by the wax is not a problem. To be completely safe for human consumption, only a small amount of additional purification would be needed.

Over time the wax does not provide significant soil stability and erosion can occur. This increases the sediment content of the runoff water (Frasier and Myers, 1983). Soil erosion can be decreased by prestabilising the soil before the application of wax or by treating the surface with a mixture of wax and an antistripping agent. By adding an antistripping agent to the wax, the weatherability of the treatment is increased by a factor of ten or more, depending on the type of antistripping agent used (Fink, 1984). Therefore, the antistripping agent can increase the lifespan of the treatment, minimise erosion and keep the water quality high for a longer period of time.

3.4.6 Working Examples

Wax-based runoff farming was used to grow two species of conifers in a semi-arid climate in the southwest USA. A sandy soil was treated with wax and a clay soil was treated with sodium chloride salt. Tree growth varied between the two species on each type of treatment. The fastest growing and healthiest trees were the Arizona cypress (*Cupressus arizonica*) on the sand-wax site. On the clay-salt site the cypress were 1-2 years behind those at the sand-wax site. However, the other species, the Quetta pine (*Pinus eldarica*), grew poorly on the sand site, with greater than 50% mortality of pines on areas with lower water treatments. The pines grew well on the clay-salt site and 24% were marketable in three years, with the remainder marketable in the fourth year (Fink and Ehrler, 1983). Therefore, the effectiveness of the water harvesting treatments is as much related to the needs and conditions of different plant species as it is to the runoff efficiency and water quality of the treatment.

Forage production of blue panicgrass (*Panicum antidotale Retz.*) was greatly increased using runoff water from a wax treated water harvesting system. Plots of panicgrass had wax-treated catchment aprons twice the size of the cropping area. The plots produced forage yields sixteen times greater than those of the control. Including the catchment area, the average per hectare yield was about five times greater than the control, in an area receiving less than 130 mm of precipitation during the growing season. Water use efficiencies were comparable to those for irrigated grass (Schreiber and Frasier, 1978). It was also found that when blue panicgrass was grown by runoff farming, nitrogen fixation occurred and more nitrogen was available to plants (Frasier and Schreiber, 1978).

Two wax-treated water harvesting systems set up in northwest Arizona, on clay loam soils with a 5-8% slope, allowed one user to winter 200 cows with calves for 5-6 months, compared to only 30-50 cows with calves without the reliable water supply. Water harvesting during drought years could remove some of the financial burden placed on farmers and agriculturalists in dry areas and possibly avoid the need to reduce the size of their base herds and crop areas (Cooley *et al.,* 1978).

3.5 Gravel-covered Membranes

The Gravel-covered plastic treatment consists of a waterproof membrane, such as thin polyethylene sheeting or asphalt-coated roofing tar paper, which is placed on the prepared catchment surface and covered with a thin layer of uniform-sized gravel. The gravel holds the membrane in place, protects it from solar radiation and provides some resistance to minor mechanical damage (Frasier, 1981). An asphalt emulsion tack coat is used in some installations to bond the membrane to the soil and/or the gravel to the membrane (Myers, 1965; cited in Frasier and Myers, 1983).

3.5.1 Biophysical Constraints

This catchment covering requires a very smooth, rock and gravel free surface. It is not dependent on specific soil types, but can't be used on a soft sub-base. It can be used in most climates on slopes less than 5% to reduce the downslope movement of gravel (Frasier and Myers, 1983).

3.5.2 Runoff Efficiency

The runoff efficiency for this type of catchment is influenced by the intensity of rainfall and the thickness of the gravel layer, as a portion of the rainfall is absorbed by the gravel and then evaporates (Frasier and Myers, 1983). Cluff (1975) stated that the runoff efficiency was between 60-80%; Frasier (1975b) estimated it to be 70-80% and Matlock and Shaw (1966; cited in Frasier and Myers, 1983) suggested that the average was 86-90%. For precipitation in excess of 2 mm, the runoff is essentially 100% (Frasier, 1981).

3.5.3 Durability/Maintenance/Lifespan

Gravel-covered membrane catchments are relatively resistant to deterioration by weathering as long as the gravel layer is maintained. If the gravel is disturbed, the membrane is susceptible to wind and sun damage. It can be punctured by animal traffic and human traffic should be kept to a minimum (Frasier and Myers, 1983).

The entire area should be examined every six months. Maintenance of the catchment consists of covering exposed plastic with left over gravel and repairing holes in the plastic immediately. With time, the gravel layer traps soil and seeds and any plant growth needs to be removed so that it will not damage the membrane (Frasier and Myers, 1983). Over time, the dust will accumulate in the gravel and reduce the runoff efficiency of the catchment. To minimise losses, the plastic should be covered with the smallest size and depth of gravel needed to provide complete cover (Cluff, 1975).

In contrast with other types of catchments, the maintenance of a properly constructed gravel-covered membrane catchment will decrease over time. With each rainfall event that is of higher intensity than the last, the gravel reorients and settles, and is more likely to remain covering the membrane evenly. The estimated life of the treatment is dependent on when the membrane needs replacing, and can be up to 25 years. The gravel can be used indefinitely (Cluff, 1975).

3.5.4 Costs

Initial costs for a gravel-covered catchment are primarily dependent on the availability of materials and the cost of the gravel. The extent of clearing and shaping of the catchment will also affect costs. Estimated costs, using 1975 prices, are projected to be around US$3,000 – $7,100/ha (Cluff, 1975). Typical labour for a 0.1ha catchment is around 64-80 hours (Frasier and Myers, 1983).

3.5.5 Water Quality

The water quality of the runoff from this type of catchment is excellent. There is no contamination of the water from the materials used and because surface erosion is not a problem, the catchment provides sediment-free water (Frasier and Myers, 1983).

3.5.6 Working Example

The Water Resources Research Centre field laboratory at the University of Arizona, USA, installed a gravel-covered membrane catchment with 6-mil polyethylene plastic. After approximately nine years, the catchment was still in excellent condition with an average runoff efficiency of 70% and was supplying approximately 2.151 Ml/ha/yr (Cluff, 1975).

3.6 Asphalt-fibreglass Membranes

The asphalt-fibreglass treatment consists of a field-fabricated membrane saturated with an asphalt emulsion. To assemble the membrane, a roll of fibreglass matting or strips of chopped matting are placed on the catchment surface and then saturated with a water-based asphalt emulsion. The emulsion soaks through the fabric and binds the membrane to the soil, with the water in the emulsion softening the fabric and allowing it to conform to surface irregularities (Frasier and Myers, 1983). After 2-10 days the asphalt is partially cured and a second coat of the emulsion is applied to seal the membrane surface (Frasier, 1980).

The asphalt hardens during the curing process and forms a semi-rigid membrane with high tear strength. The asphalt also cements the fabric threads and seals the pore spaces (Frasier and Myers, 1983). This treatment is being used extensively to provide drinking water for livestock and wildlife in the USA (Frasier, 1981).

3.6.1 Biophysical Constraints

Asphalt-fibreglass catchments are not restricted to soil type and have been successful on rough surfaces where other treatments have failed. The treatment has worked on relatively loose sandy soils, soils with a high percentage of swelling clays and surfaces with large buried rocks or exposed rock outcroppings. Climate is not an important factor as the treatment has survived in hot arid regions, cold mountainous regions and the humid tropics (Frasier and Myers, 1983). Natural slopes of 5-20% are suitable for this type of catchment (Myers and Frasier, 1974).

3.6.2 Runoff Efficiency

Asphalt-fibreglass catchments have very high runoff efficiency. Cluff (1975) estimated the runoff to be 85-95% whereas Frasier *et al.,* (1979) estimated runoff efficiency greater than 95%, where rainfall of less than 1.3 mm will produce runoff.

3.6.3 Durability/Maintenance/Lifespan

This treatment is highly resistant to mechanical damage and deterioration by weathering processes. The membrane takes 6-12 months to become semi-rigid and this is when maintenance is the most important. Care is needed to ensure that all lap joints and edges are properly sealed to prevent wind damage (Frasier and Myers, 1983).

When exposed to sunlight the asphalt slowly oxidises. Some catchments are coated with a pigmented paint when constructed to reduce the rate of asphalt oxidation and deterioration, and this increases the life of the treatment. If the membrane is installed without the protective coating, a new seal coat will be required over the entire catchment every 3-6 years. With the protective coating, the treatment can last 10 years or more before resealing is needed. However, the cost of the protective coating for asphalt surfaces is relatively expensive, more than US$12,000/ha (1980 prices) (Frasier, 1980).

Once the membrane is semi-rigid, it is highly resistant to wind damage or animals walking on the surface. However, rodents can chew holes through the membrane and soil can accumulate on the lining surface. Seeds can germinate and grow in the soil and all plants need to be removed. If the white fibreglass is visible on the catchment surface a new seal coat is needed. To ensure bonding between the seal coat and the oxidised surface, the catchment should be given a light tack coat of cutback asphalt before the new seal coat is applied (Myers and Frasier, 1974).

Between seal coats, maintenance is simple and would only need three man-hours/year (Myers and Frasier, 1974). With proper maintenance, the projected life of the treatment is in excess of 20 years (Frasier and Myers, 1983).

Nine asphalt-fibreglass catchments, constructed on field test sites since 1962, have shown no significant deterioration or mechanical damage by wind or animals after 12 years. They were fabricated onsite by saturating glass matting with low viscosity asphalt emulsion and then sealing with roofing grade asphalt emulsion. Eight of the nine catchments have shown excellent performance, despite almost no maintenance (Myers and Frasier, 1974).

3.6.4 Costs

Myers and Frasier (1974) found that initial construction costs, including site preparation and labour, were less than $15,000/ha. For a 0.09 ha catchment, the cost of the catchment, excluding site selection, surveying and fencing, was estimated to be US$1,300. Installation time for the asphalt-fibreglass surface was around 24-30 hours for a 0.1 ha catchment (Frasier and Myers, 1983).

3.6.5 Water Quality

The water produced from an asphalt-fibreglass catchment is discoloured by oxidised asphalt, especially in arid regions (Myers and Frasier, 1974). The water can be used for livestock, but may not be suitable for human consumption without further purification (Frasier and Myers, 1983).

3.7 Other Ground Covers (Concrete, Sheet Metal, Butyl Rubber)

Ground cover catchments consist of an impervious membrane, such as concrete, sheet metal and butyl rubber, and have very high durability, runoff efficiency and need little maintenance. However, initial costs are very high. These catchments are not as common because of this high cost and sophisticated equipment or a high amount of labour is often needed to construct them (Frasier and Myers, 1983).

Artificial rubber membranes were used extensively in the 1950s and 60s. They were relatively easy to install, but were not durable over surface irregularities that induced localised tensile stresses and therefore deteriorated quickly on rough surfaces (Frasier and Myers, 1983).

Sheet metal coverings use the principle of a house roof catchment. They consist of an above ground wooden framework in the shape of an inverted roof, covered in corrugated sheet metal. Smaller versions are used for stock and wildlife drinking water (Frasier and Myers, 1983).

3.7.1 Biophysical Constraints

These treatments can be used on most soils and concrete and sheet metal catchments need a minimum of site preparation. Artificial rubber catchments need a smooth base to minimise localised tension on the membrane. They are very durable in most climates, although wind characteristics need to be considered before installing a sheet metal structure, as wind can get underneath the sheeting and cause damage (Frasier and Myers, 1983). These treatments can be used on slopes of up to 20% (Frasier, 1980).

3.7.2 Runoff Efficiency

Runoff efficiencies for these catchments are relatively high. Sheet metal catchments have runoff efficiencies of 95-100% and artificial rubber membranes are 98-100% efficient. Concrete catchments are less efficient, with 60-85% runoff. This is due to the concrete soaking up a portion of the rainfall and shrinkage cracks occurring in the surface if large areas are being covered. These cracks reduce the amount of runoff from the surface (Frasier and Myers, 1983).

3.7.3 Durability/Maintenance/Lifespan

These materials are very durable and are fairly resistant to all weathering conditions. Sheet metal needs to be galvanized or treated to prevent corrosion and must be anchored securely at all times to prevent wind damage. Butyl rubber is susceptible to wind damage and rodents burrowing under the membrane if the edges are not properly secured or buried. If there are holes in the rubber membrane, high winds can dislodge the entire cover (Mickelson, 1975). Because of this, rubber catchments need to be inspected frequently and repaired immediately where needed. The estimated lifespan of concrete, sheet metal and butyl rubber catchments are >25 years, >20 years and 10-20 years respectively (Frasier and Myers, 1983).

3.7.4 Costs

These materials have high initial installation costs. Frasier and Myers (1983) estimated the cost for a concrete catchment is $12,000-24,000/ha for a 4-inch slab, $9,500-18,000/ha for a sheet metal catchment and $6,000-12,000/ha for artificial rubber catchments. These figures are based on 1981 prices and are in US dollars.

3.7.5 Water Quality

The water running off these catchments is of high quality and contains very little sediment or impurities. Concrete and butyl rubber catchments often have more sediment runoff than the sheet metal catchment as more windborne dust or fine soil accumulates on the ground surface (Mickelson, 1975).

4. Summary

This section includes tables that summarise characteristics for different water harvesting treatments found in the literature. Table 3 is a complete summary from a number of different sources and Tables 4, 5, 6 and 7 have been sourced directly from the literature.

Table 3. Characteristics of Different Water Harvesting Treatments Summarised from the Literature

	Runoff Efficiency	**Lifespan**	**Soils**	**Slope Gradient**	**Initial Treatment Costs**
Compacted Soil	33% (Laing, 1981) 30-60% (Cluff, 1975)	5-10 yrs (Frasier, 1975)	>25% clay (Laing, 1981) clay soils (Burdass, 1975) non-expanding clays (Frasier, 1981)	1 in 10 or 1 in 20 (Myers, 1967) <5% (Frasier and Myers, 1983)	US$445 to $700/ha (1974) (Cluff, 1975) A$500/ha (1980) (Laing, 1981)
Salt-Treated	50-75% (Frasier and Myers, 1983) 55-89% (Frasier *et al.,* 1987) >50% (Cluff, 1975) 52.5% (Dutt and McCreary, 1975)	3-5 yrs (Frasier, 1975) 3 yrs (Frasier *et al.,* 1987)	>15% clay (Frasier *et al.,* 1987)	2-4% (Dutt and McCreary, 1975)	US$2,500 to $7,000/ha (1984) (Frasier *et al.,* 1987) US$900 to $1,480/ha (1974) (Cluff, 1975)
Paraffin Wax	80-95% (Frasier and Myers, 1983) 87% (Fink *et al.,* 1980) >80% (Frasier *et al.,* 1979) 80-99% (Frasier, 1981) 90% (Cooley *et al.,* 1987) 90% (Fink *et al.,* 1973) 80-95% (Frasier, 1980)	5-10 yrs (Frasier and Myers, 1983) >7 yrs (Fink *et al.,* 1980) RE dropped after 3-5 yrs (Frasier, 1981) 5-8 yrs (Frasier, 1975)	<20% clay (Frasier and Myers, 1983) coarser, sandy soils (Frasier, 1980)	3-5% (Frasier and Myers, 1983)	US$6,000 to $12,000/ha (1981) (Frasier and Myers, 1983) US$3,900/ha (1974) (Cooley *et al.,* 1978)
Gravel-Covered Plastic	70-80% (Frasier, 1975) 86-90% (Matlock and Shaw, 1966) 100% over 2 mm rainfall (Frasier, 1981) 70% (Cluff, 1975)	15-20 yrs (Frasier and Myers, 1983)	most soils (Frasier and Myers, 1983)	<5% (Frasier, 1983)	US$3,000 to $7,100/ha (1975) (Cluff, 1975)
Ashalt-Fibreglass	95-100% (Frasier and Myers, 1983) >95% (Frasier, 1980) >95% (Cluff, 1975)	>20 yrs (Frasier and Myers, 1983) >10 yrs (Frasier, 1980)	most soils (Frasier and Myers, 1983)	5-20% (Myers and Frasier, 1974)	US$15,000/ha (1974) (Myers and Frasier, 1974)
Concrete	60-85% (Frasier and Myers, 1983) 60-90% (Frasier, 1981)	>25 yrs (Frasier and Myers, 1983)	most soils (Frasier and Myers, 1983)	up to 20% (Frasier, 1980)	US$120,000 to $240,000/ha (1981) (Frasier and Myers, 1983)
Artificial Rubber	60-90% (Frasier, 1981) 98-100% (Frasier and Myers, 1983) 56% (Mickelson, 1975)	10-20 yrs (Frasier and Myers, 1983)	most soils (Frasier and Myers, 1983)	up to 20% (Frasier, 1980)	US$60,000 to $120,000/ha (1981) (Frasier and Myers, 1983) US$24,000 to $36,000 (1966) (Lauritzen and Thayer, 1966; cited in Frasier, 1975)
Sheet Metal	95-100% (Frasier and Myers, 1983)	>20 yrs (Frasier and Myers, 1983)	most soils (Frasier and Myers, 1983)	up to 20% (Frasier, 1980)	US$95,000 to $180,000/ha (1981) (Frasier and Myers, 1983) US$24,000 to $36,000 (1967) (Lauritzen, 1967; cited in Frasier, 1975)

Table 4. Threshold Rainfall and Runoff for Various Treatments at the Granite Reef Test Site. (Source: Frasier, 1975a) (Threshold Rainfall is the Minimum Rainfall Needed to Produce Runoff. (Source: Li and Gong, 2002))

Treatment	**Length of Study** *(Years)*	**Threshold Rainfall** *(Millimetres)*	**Runoff Efficiency** *(Percent)*
Uncleared watersheds	10	3.1	22
Cleared watersheds	10	2.7	32
Smoothed untreated	12	2.3	36
Ridge and furrow	9	2.2	42
Sodium carbonate	5	2.2	47
Silicone water repellent	10	1.8	81
Single-phase asphalt	9	1.7	71
Silicone water repellent plus stabiliser	3	1.2	88
Gravel-covered sheeting	7	1.2	92
Concrete	6	1.1	84
Paraffin wax water repellent	2	0.5	95
Two-phase asphalt	11	0.5	96
Aluminium foil	10	0.4	88
Asphalt fibreglass	7	0.4	98
Butyl	12	0.3	90
Polyethylene	4	0.2	92
Chlorinated polyethylene	6	0.1	95
Polyvinyl fluoride	2	0.0	100

Table 5. Water Costs for Various Water Harvesting Treatments. (Source: Frasier, 1975a)

Treatment	**Runoff Efficiency** *(Percent)*	**Estimated Life of Treatment** *(Years)*	**Initial Treatment Cost†** *(Dollars/m)*	**Annual Prorated cost†** *(Dollars/m)*	**Water Cost in a 500 mm Rainfall Zone** *(Dollars/1,000L)*
Land clearing	20-30	5-10	0.01-0.02	<0.01	0.08-0.12
Soil smoothing	25-35	5-10	0.04-0.06	0.01-0.02	0.07-0.19
Silicone water repellents	50-80	5-8	0.1-0.15	0.02-0.03	0.06-0.19
Paraffin wax	60-90	5-8	0.25-0.33	0.04-0.08	0.13-0.39
Concrete	60-80	20	1.67-4.2	0.14-0.37	0.5-1.73
Gravel-covered sheeting	70-80	10-20	0.42-0.58	0.03-0.08	0.12-0.34
Asphalt fibreglass	85-95	5-10	0.83-1.67	0.12-0.4	0.35-1.32
Artificial rubber	90-100	10-15	1.67-2.5	0.18-0.34	0.49-1.05
Sheet metal	90-100	20	1.67-2.5	0.14-0.32	0.4-0.68

† Based on the life of the treatment at 6% interest.

Table 6. Summary of Analysis of Elements in Parts per Million (ppm) from Samples Collected From Various Water Harvesting Catchment Surfaces. (Source: Frasier, 1980)

		Catchment Surface				
Constituent	**Asphalt**	**Paraffin Wax**	**Butyl**	**Silicone Water Repellent**	**Galvanised Steel**	**Public Health Standard**
Cadmium	-	-	<0.001	-	<0.008	0.01
Calcium	0.5-35.0	6.4-46.0	2.1-32.0	3.8-14.0	ND	-
Chromium	<0.002	<0.009	<0.02	<0.003	<0.01	0.05
Iron	<0.0008	<0.009	<0.02	<0.003	<0.01	0.3
Lead	<0.01	<0.02	<0.03	<0.02	<0.01	0.05
Magnesium	0.1-6.0	0.7-6.0	0.4-2.0	0.5-2.0	ND	-
Mercury	<0.0007	<0.0009	<0.001	<0.0008	<0.0005	0.002
Potassium	0.3-6.0	1.2-16.0	0.7-2.0	0.9-5.0	ND	-
Sodium	0.2-12.0	0.4-8.0	0.5-1.0	0.9-9.0	ND	-
Zinc	<0.004	<0.003	<0.01	<0.0001	0.2	0.15

Table 7. Water Costs for Various Water Harvesting Treatments. (Source: Frasier, 1975b)

Treatment	**Runoff (%)**	**Estimated Life of Treatment (years)**	**Initial Treatment Cost ($/yd[1])**	**Annual Amortised Cost ($/yd[1])**	**Water Cost in a 20-inch Rainfall Zone ($/1,000 gal)**
Rock outcropping	20-40	20-30	<0.01	<0.02	0.22-0.45
Land clearing	20-30	5-10	0.01-0.02	<0.01	0.30-0.45
Soil smoothing	25-35	5-10	0.05-0.07	0.01-0.02	0.25-0.71
Sodium dispersant[2]	40-70	3-5	0.07-0.12	0.01-0.02	0.13-0.45
Silicone water repellents[3]	50-80	3-5	0.12-0.18	0.02-0.04	0.22-0.71
Paraffin wax[4]	60-90	5-8	0.30-0.40	0.05-0.10	0.50-1.49
Concrete	60-80	20	2.00-5.00	0.17-0.44	1.89-6.53
Gravel covered membranes	70-80	10-20	0.50-0.70	0.04-0.10	0.45-1.27
Asphalt fibreglass[5]	85-95	5-10	1.00-2.00	0.14-0.48	1.31-5.00
Artificial rubber[6]	90-100	10-15	2.00-3.00	0.21-0.41	1.87-4.00
Sheet metal[7]	90-100	20	2.00-3.00	0.17-0.26	1.51-2.57

[1] Based on the life of the treatment at 6% interest.

[2] Cluff, 1975.

[3] Myers and Frasier, 1969.

[4] Fink *et al.,* 1973.

[5] Myers and Frasier, 1974.

[6] Lauritzen and Thayer, 1966.

[7] Lauritzen, 1967.

5. Concluding Remarks

In this report we have reviewed the historical examples of water harvesting. Most of the documented examples are local and microcatchment systems not orientated to the sale of water to the water market. However, there is sufficient experience in water harvesting that it should be further considered as a mechanism for providing additional water for streams that are under stress.

The adoption of catchment scale water harvesting has been blocked by several factors in the past:

1. The relative security of alternative sources of water.
2. The low price of water.
3. The limitations of water market to consider enhanced runoff.
4. Institutional arrangements and rights that exclude or limit the ability of land managers to sell additional runoff.

In Australia the first two of these items have seen rapid change in recent years with the emergence of water allocation and water security as major rural issues. Also there have been major changes in the price of water associated with developing water markets.

The future steps in developing the concept of Water Farms should include evaluation of the economics of Water Farms. It is likely that there are institutional barriers to enterprises selling enhanced runoff from a land unit for particular jurisdictions. Thus there are still several steps to be in place before large scale water farms focussed on providing additional streamflow become a reality.

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Appendix

Search Strategy

Step 1. Searched Web of Science, a branch of Web of Knowledge – http://isi2.isiknowledge.com/ in December 2002. Database search displayed articles from 1986 - 2002.

Keyword: “water harvesting” – Laryea, 1992; Carter and Miller, 1991; Oron and Enthoven, 1987; Emmerich *et al.,* 1987; Rees *et al.,* 1991.

Keyword: “Rainwater harvesting” – Li and Gong, 2002; Li *et al.,* 2001; Young *et al.,* 2002.

Keyword: “Runoff farming” – Benhur, 1991; 1975; Fink and Ehrler, 1986; Lovenstein *et al.,* 1991.

Keyword: Runoff AND sealing - Zhang *et al.,* 1998; Le Bissonnais and Singer, 1992; Shainberg and Levy, 1994; Lentz *et al.,* 1992.

Source and citation searches were done on each of these articles, and further references were obtained.

Step 2. Searched Google – http://www.google.com/:

Keywords: “rainwater harvesting” – UNEP, 2000; Faillace, 1999.

Keywords: “roaded catchment” – Frasier, 1975; Lantzke, 2002.

Step 3. Searched Igenta – http://www.ingenta.com/:

Keyword: surface AND “water harvesting” – Lavee *et al.,* 1997.

Step 4. Searched CSIRO Library book catalogue – “water harvesting” – Boers, 1994; Oweis *et al.,* 1999; Mielke and Dutt, 1981.

Step 5. References recommended to me - Fink *et al.,* 1980; Frasier, 1980; Frasier *et al.,* 1987; Frasier *et al.,* 1979; Frasier and Myers, 1983; Schreiber and Frasier, 1978.

Step 6. Steps 1 to 4 gave me a list of references. I then searched for the articles. Recent references were found through electronic journals on the CSIRO Library database. References dated before 1995 were found through manual searches of the CSIRO Library network.

Step 7. Manual citation searches were then carried out from the bibliographies of all articles I found.

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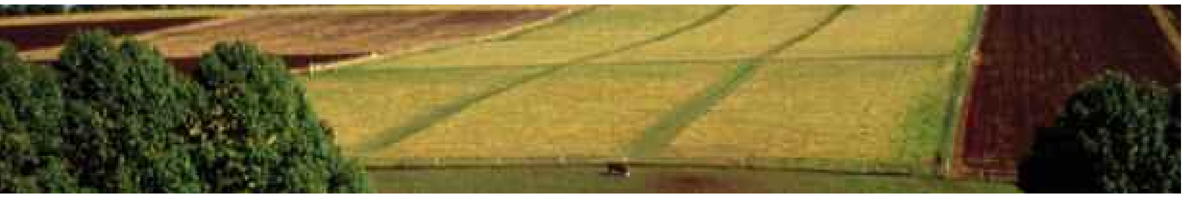

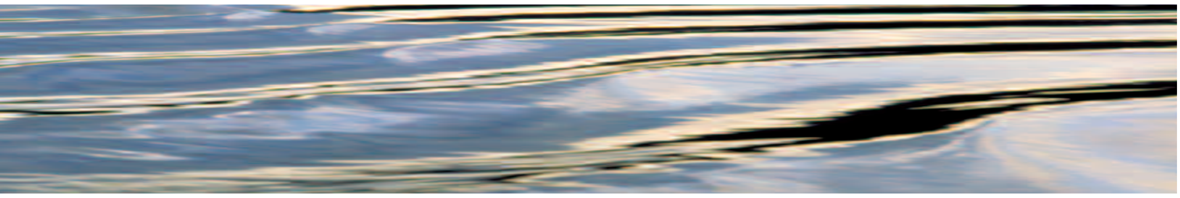

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