Maximising Water Storage in South-East Queensland Reservoirs: Evaluating the Potential of Runoff and Infiltration Enhancement

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The Urban Water Security Research Alliance (UWSRA) is a $50 million partnership over five years between the Queensland Government, CSIRO’s Water for a Healthy Country Flagship, Griffith University and The University of Queensland. The Alliance has been formed to address South-East Queensland's emerging urban water issues with a focus on water security and recycling. The program will bring new research capacity to South-East Queensland tailored to tackling existing and anticipated future issues to inform the implementation of the Water Strategy.

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FOREWORD

Water is fundamental to our quality of life, to economic growth and to the environment. With its booming economy and growing population, Australia's South-East Queensland (SEQ) region faces increasing pressure on its water resources. These pressures are compounded by the impact of climate variability and accelerating climate change.

The Urban Water Security Research Alliance, through targeted, multidisciplinary research initiatives, has been formed to address the region's emerging urban water issues.

As the largest regionally focused urban water research program in Australia, the Alliance is focused on water security and recycling, but will align research where appropriate with other water research programs such as those of other SEQ water agencies, CSIRO's Water for a Healthy Country National Research Flagship, Water Quality Research Australia, eWater CRC and the Water Services Association of Australia (WSAA).

The Alliance is a partnership between the Queensland Government, CSIRO's Water for a Healthy Country National Research Flagship, The University of Queensland and Griffith University. It brings new research capacity to SEQ, tailored to tackling existing and anticipated future risks, assumptions and uncertainties facing water supply strategy. It is a $50 million partnership over five years.

Alliance research is examining fundamental issues necessary to deliver the region's water needs, including:

- ensuring the reliability and safety of recycled water systems.
- advising on infrastructure and technology for the recycling of wastewater and stormwater.
- building scientific knowledge into the management of health and safety risks in the water supply system.
- increasing community confidence in the future of water supply.

This report is part of a series summarising the output from the Urban Water Security Research Alliance. All reports and additional information about the Alliance can be found at http://www.urbanwateralliance.org.au/about.html.

C. Davis

Chris Davis
Chair, Urban Water Security Research Alliance

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1. INTRODUCTION

Unprecedented drought conditions and a growing population are putting pressure on the water supplies of south-east Queensland (SEQ) and water management authorities are assessing all possible means by which to create a sustainable water supply in the region. This report has been prepared for the SEQ Urban Water Security Research Alliance for the purposes of assessing the potential for runoff and infiltration enhancement treatments to increase the volume of water delivered to the major storages in SEQ. This report forms one of a group of reports which each assess the applicability of different evaporation mitigation techniques to south-east Queensland water supply systems.

2. MECHANISM FOR MAXIMISING WATER STORAGE IN RESERVOIRS

One means by which it is possible to increase the amount of water in a reservoir is to increase the amount of surface runoff from the catchment. There are many runoff enhancement techniques and these all aim to decrease the permeability of soil, thereby increasing the proportion of rainfall that becomes surface runoff. It is worth noting that the extra water delivered to the storage is equivalent to a reduction in evaporation and transpiration from the catchment as these are the only 'loss' pathways in the system. This is illustrated using a simple water balance in Table 1. In smaller storages (e.g. farm dams), where subsurface delivery of water is not important, the extra water is equivalent to the increase in runoff only.

Table 1: Water balance table for a hypothetical hill slope showing how the extra water delivered to a reservoir in a catchment with a runoff enhancement method applied is a result of reductions in evaporation and transpiration.

	Original state	Runoff enhanced	
Rainfall	100 mm	100 mm	(Input)
Surface Runoff	20 mm	70 mm	(Captured)
Sub-surface drainage	40 mm	20 mm	(Captured)
Evaporation and transpiration	40 mm	10 mm	(Lost)
% Captured	60%	90%	
% Lost	40%	10%	

The term runoff in this report is meant to include the drainage flow from the soils as well as the surface runoff. A simple water balance at any point within the catchment is given by:

$$RO = SRo + D = P - Et + \Delta S \qquad \text{Equation 1}$$

where -

RO	is the total runoff to the reservoir (m)
SRo	is the surface runoff (m)
D	is the subsurface drainage (m)
P	is the net precipitation to the land surface (m)
Et	is the evapotranspiration (m)
ΔS	is the change in soil storage (m)

The amount of water that infiltrates into the soil ($I = P - SRo$) can be changed by reducing the infiltration capacity of the soil. If we can reduce the amount infiltrating into the soil then the amount of surface runoff will increase.

Alternatively, another means by which to increase the delivery of water to dams could be through the enhancement of drainage, or infiltration, at different locations in the catchment. Such techniques aim to increase the amount of water moving through the soil profile at depths below the root zone. In this way transpiration losses are reduced and any possible evaporation losses from surface storages (i.e. farm dams) which fill from surface runoff are minimised.

3. OVERVIEW OF EXISTING STUDIES

Runoff enhancement techniques have been used for thousands of years (Myers, 1967) to increase water supply. Methods utilised have included clearing, smoothing and compacting, and application of surface covers. The aim of this section is to give a brief over view of these techniques and their effectiveness. Those interested in a detailed review are directed to the extensive review of Richardson *et al.* (2004), from which much of the information below has been extracted.

Surface treatments for runoff enhancements can be categorised in four main groups:

1. Surface compaction
2. Salt treatments
3. Wax sealants
4. Membranes and covers

Surface treatments for enhancing infiltration usually involve the use of swale systems which aim to trap surface runoff as it moves down the hill slope and direct it into the soil profile.

It is worth noting that application of these treatments (excluding the swale systems) assumes that existing land use is discontinued. Other uses, such as grazing, will severely limit the effectiveness of treatments.

A brief description of these techniques and studies looking at their effectiveness is given below. In most studies the effectiveness of the runoff enhancement technique is measured as a ‘runoff efficiency’ which is defined as the percentage of rainfall that becomes runoff. Most studies only regard the change in surface runoff as being important because they are small scale localised studies, they do not consider changes to sub-surface water delivery as this is usually not an important factor. In our analysis below we are assessing applicability at a much larger scale where sub-surface processes are also important, so runoff efficiency numbers are not directly applicable. We present these numbers as a guide to the relative differences between treatments only. In their comprehensive review Richardson *et al.* (2004) also present the costs associated with different treatments but they make no attempt to adjust to today’s prices or to work out the price in Australian dollars. We have made such adjustments to the studies presented in this review using an inflation calculator and currency exchange rates. Costs from studies in the USA and Australia were converted to 2007 dollars using the following online inflation calculators:

USA - http://www.westegg.com/inflation/

Australia - http://www.rba.gov.au/calculator/calc.go

Conversion to Australian dollars was made on the assumption that one Australian dollar buys 0.9 US dollars.

3.1. Surface compaction

A cleared and compacted soil surface is one of the cheapest and simplest means by which to enhance runoff. To be most effective, compaction requires soils to have clay contents in excess of 25% (Laing, 1981). In some soil types, such as duplex soils, inversion of the soil profile may be possible but this will greatly increase costs (Laing, 1981). Compaction can increase erosion, therefore it is recommended that slopes should be less than 5% and that continuous slopes should not exceed 100m (Frasier and Myers, 1983). Cluff (1975) found runoff efficiencies of 30-60% from this technique while Laing (1981) found efficiencies of 33%. Following the conversions outlined above to attain costs in today's prices, Cluff (1975) estimates costs of between $2,280-$3,600/ha and Laing (1981) $1,700/ha. Frasier (1975) predicts the lifespan of compaction to be about 5-10 years.

3.2. Salt treatments

Application of certain salts to the soil surface can be used to decrease infiltration in some soils. Sodium in the form of chloride or carbonate can break down soil aggregates and form surface seals. The clay content of the soils is vital to the success of this method and Frasier *et al.* (1987) suggests that soils should be at least 15% clay. Salt treatments do not stabilise the soil therefore slopes should be less than 5% (Dutt and McCreary, 1975). Runoff efficiencies of between 40-75% are reported by Cluff (1975), while Myers (1967) reports 70%. Frasier *et al.* (1987) estimated costs of salt treatment to be between $5,700 - $16,000/ha plus $690-$5,000/year for maintenance. Cluff (1975) estimates costs to be $4,600 - $6,800/ha. The lifespan of salt treatments is likely to be between 3-5 years (Frasier, 1975).

3.3. Wax sealants

Application of wax to a soil surface can also enhance runoff. The treatment involves applying a wax with a low melting temperature (i.e. paraffin wax) in flake form to the surface. On warm days the wax flakes melt into the top 1-2cm of the soil profile coating the particles with a thin water repellent film. The warm climate in south-east Queensland would favour the use of such techniques. Runoff efficiencies from wax treatments are generally quite high. Frasier *et al.* (1979) reports runoff efficiencies of 80-95% while Fink *et al.* (1980) present results showing runoff efficiencies of around 87%. The projected life of wax treatments is 5-10 years (Frasier and Myers, 1983). Frasier and Myers (1983) estimate costs for wax treatments of $16,550 - $33,100/ha, while Cooley *et al.* (1978) estimate costs to be $20,000/ha.

3.4. Membranes and covers

Application of membrane and covers of different materials have also been shown to be effective in increasing runoff. Membranes and covers that have been used include polyethylene sheeting, rubber, asphalt-fibreglass, concrete and sheet metal (Richardson *et al.*, 2004). Such techniques are generally suited to only small applications (i.e. <1 ha) therefore we will not consider them any further in this report where we are considering broad scale treatments. Readers interested in more information are again directed to the review of Richardson *et al.* (2004).

3.5. Swales

One problem with reducing infiltration and increasing surface runoff is that this may result in increased erosion due to higher flow velocities in the channels feeding the reservoir. This could lead to increased sediment delivery to the reservoirs and during high flow events the increased possibility of overtopping events. Another approach to increasing the runoff is to increase the infiltration and thus increase the drainage component of the runoff. This approach has been used in urban situations to intercept overland flow (Dietz, 2007). When swales are formed across the landscape the infiltration capacity of the soil is increased by mechanical ripping of the soil profile.

Coombes and Kuczera (2000) estimate the cost of contour bank swale construction at $30/m. Assuming swales are spaced at 20m, 40m and 80m intervals we arrive at costs of $15,000/ha, $7,500/ha and $3,750/ha, respectively. An alternative design is to add trees to the swale although this will incur additional costs. Assuming tree planting costs $2/tree for seedlings (including labour) and we have a spacing of 2m between trees then the cost is $1/m of swale. Therefore, for treed swales spaced at 20m, 40m and 80m intervals we arrive at costs of $15,500/ha, $7,750/ha and $3,875/ha, respectively.

Swales will also require fencing on both sides to ensure stock do not compact the swale soil or destroy seedlings. We will assume 1,000m of fencing per hectare for swales spaced at 20m, 500m for swales spaced at 40m and 250m for swales spaced at 80m. Estimates for fencing costs are $4/m (SCA, 2006), therefore fencing costs are $4,000/ha, $2,000/ha, and $1,000/ha for the 20m, 40m and 80m spaced swales respectively. We will assume that annual costs of maintenance and loss of production will be $500/ha, $250/ha and $125/ha, for 20m, 40m and 80m spaced swales respectively. We will assume a lifespan of 10 years for bare swales and 20 years for swales with trees. Unlike the surface treatments it is assumed that existing land-use continues after swales have been added to the landscape.

4. DESKTOP ANALYSIS DESCRIPTION

The analysis described in this section is based around assessing the potential for runoff enhancement techniques to maximise inflow to the Wivenhoe, Somerset and North Pine reservoirs.

4.1. Definition of suitable areas

The ESRI ArcGIS, version 9.2, software product was used to develop spatial entities and perform analysis of potential runoff enhancement areas in the Wivenhoe, Somerset, and North Pine reservoir catchments. A land suitability classification was developed within ten 1 km zones buffered from each analysis reservoir. It was decided that distances further than this would involve significant additional costs in getting water to the storage and as such they were not suitable.

The next step was to identify soils with suitable clay contents for each treatment. For soil compaction, salt treatment and wax treatment techniques the required clay contents were, >25%, >15% and <20%, respectively. A soil clay content grid, originally developed for the National Land & Water Resources Atlas (NLWRA - http://nlwra.gov.au), was used to identify suitable land for each enhancement technique.

A slope grid was derived from the south-east Queensland (SEQ) digital elevation model (DEM) to identify slopes suitable for enhancement techniques (i.e. <5%). The reclassified clay and percent slope grids were then converted into layers and combined using a union operation in ArcGIS to create a layer identifying suitable slope and clay content for each technique.

Finally it was necessary to identify land use types where runoff enhancement techniques could be employed. For this we chose areas delineated as grazing land in the Queensland Land Use Mapping Project (QLUMP) data set (Witte *et al.*, 2006). Grazing land is selected as it represents a land use where vegetation cover is already very low and potential income loss is less than for other land uses such as horticulture. The slope and clay content layers were then combined with the land use layer to identify suitable land available for runoff enhancement. The new layer was also intersected with the buffer zones. The area in square metres was then calculated for the final layer for each technique so that the area of suitable land within each buffer zone could be calculated. The sources of data used in this desktop analysis are shown in Table 2.

Table 2: **Data sources used for analysis of runoff enhancement techniques.**

Dataset Name	Year	Purpose	Source	Scale
SEQ DEM	Supplied 2008	Definition of sub-catchments and stream networks	Qld NRW	25m grid cells
QLUMP land use	1999	Identify grazing lands and reservoirs in analysis catchments	Qld NRW	1:100,000
Qld Basinsubarea	2006	Demarcate analysis region	Qld NRW	1:100,000
Soil clay content for Australian areas of intensive agriculture (A-horizon – Top-soil)	2001	Develop % clay classes for each scenario	NLWRA	1.1 km grid cells

For the swales we assume that these will be implemented across the whole catchment so no spatial analysis was undertaken.

4.2. Definition of treatment costs

For the purposes of this desktop study the cost of the treatment is taken as the average of the range of costs reported in the literature. For soil compaction we use a cost of $3,000/ha which includes $350/ha for ongoing maintenance. Lifespan is assumed to be seven years. For salt treatment we use $10,300/ha plus $2,750/year/ha for maintenance. This results in a total cost for the four year lifespan of this product of $3,260/ha. For paraffin wax we use a cost of $25,000/ha including maintenance over its eight year lifespan. The soil slope and costs used in this desktop study are summarised in Table 3.

Estimates for the swale construction and fencing are that it will cost approximately $19,000/ha, $9,500/ha and $4,750/ha, for bare swales at 20m, 40m and 80m intervals, respectively and $19,500/ha, $9,750/ha and $4,875/ha for treed swales at 20m, 40m and 80m intervals, respectively. We assume that annual costs of maintenance and loss of production will be $500/ha, $250/ha and $125/ha, for 20m, 40m and 80m spaced swales respectively. We will assume a lifespan of 10 years for bare swales and 20 years for swales with trees. Annual treatment costs are given in Table 3.

An additional component to be factored into the cost analysis is the price of the land. This does not apply to the swales as the existing land-use is assumed to continue with minimal disruption. For the surface treatments we will assume that land is valued at $7,000/ha and we will use the capital write off period of 40 years as used by the Australian Tax Office.

Table 3: Clay content, slope, lifespan and treatment costs for the three runoff enhancement techniques analysed. Lifespan and costs of bare and treed swales at different spacing are also shown.

Method	Required clay content	Required slope	Assumed lifespan	Treatment cost	Assumed treatment cost per year*
Soil compaction	>25%	<5%	7 years	$3,000 / ha	$430 / ha / yr
Salt treatment	>15%	<5%	4 years	$13,050 / ha	$3,260 / ha / yr
Paraffin wax	<20%	<5%	8 years	$25,000 / ha	$3,125 / ha / yr
Swale bare – 20 m	-	-	10 years	$19,000 / ha	$2,400 / ha / yr
Swale bare – 40 m	-	-	10 years	$9,500 / ha	$1,200 / ha / yr
Swale bare – 80 m	-	-	10 years	$4,750 / ha	$600 / ha / yr
Swale treed – 20 m	-	-	20 years	$19,500 / ha	$1,975 / ha / yr
Swale treed – 40 m	-	-	20 years	$9,750 / ha	$990 / ha / yr
Swale treed – 80 m	-	-	20 years	$4,875 / ha	$495 / ha / yr

*See text in Section 3 for assumptions and conversions.

4.3. Water balance modelling

A water balance model based on that of Cook *et al.* (2008) was used to model the water balance of the soil. This model was used because it employs the Deardoff (1978) force-restore mechanism at the soil surface to give a more accurate estimate of soil evaporation. This higher accuracy is required in this model because the soil surface is being modified by the treatments.

Maps of the available water capacity (AWC) and saturated hydraulic conductivities (Ks) of A and B soil horizons for the catchments (Figure 1) were used to generate 14 unique soils (Table 4). The source for this data was the National Land and Water Resources Atlas (NLWRA).

From these data we derived the depth of the soil layers, sorptivity (*So*), saturated water content (θ_s), field capacity (θ_{FC}) and permanent wilting point (θ_{PWP}) using information on soils of similar textures. The depth of the surface layer for the force-restore process was taken to be 0.1m, which is a reasonable depth for drying front penetration based on the macroscopic capillary length scale.

For the three treatments the surface layer (force-restore layer) properties were modified and therefore the water content values were increased or decreased by the values in Table 5. The sorptivity for different treatments was calculated by dividing by the number in Table 5. These changes were based on information from Cook *et al.* (1986) and Cook *et al.* (2006).

Table 4: **Soil properties for the 14 unique soils identified from soil data in maps of Figure 1.**

Soil No.	AWC (m)		Ks (m day^{-1})	
	A horizon	B horizon	A horizon	B horizon
1	0.031	0.030	2.277	0.023
2	0.031	0.030	2.277	0.228
3	0.031	0.030	2.277	2.277
4	0.031	0.030	2.277	22.77
5	0.031	0.075	2.277	2.277
6	0.031	0.075	2.277	22.77
7	0.031	0.125	2.277	0.023
8	0.031	0.125	2.277	0.228
9	0.031	0.125	2.277	2.277
10	0.031	0.030	22.77	2.277
11	0.031	0.030	22.77	22.77
12	0.031	0.075	22.77	2.277
13	0.031	0.075	22.77	22.77
14	0.062	0.075	22.77	2.277

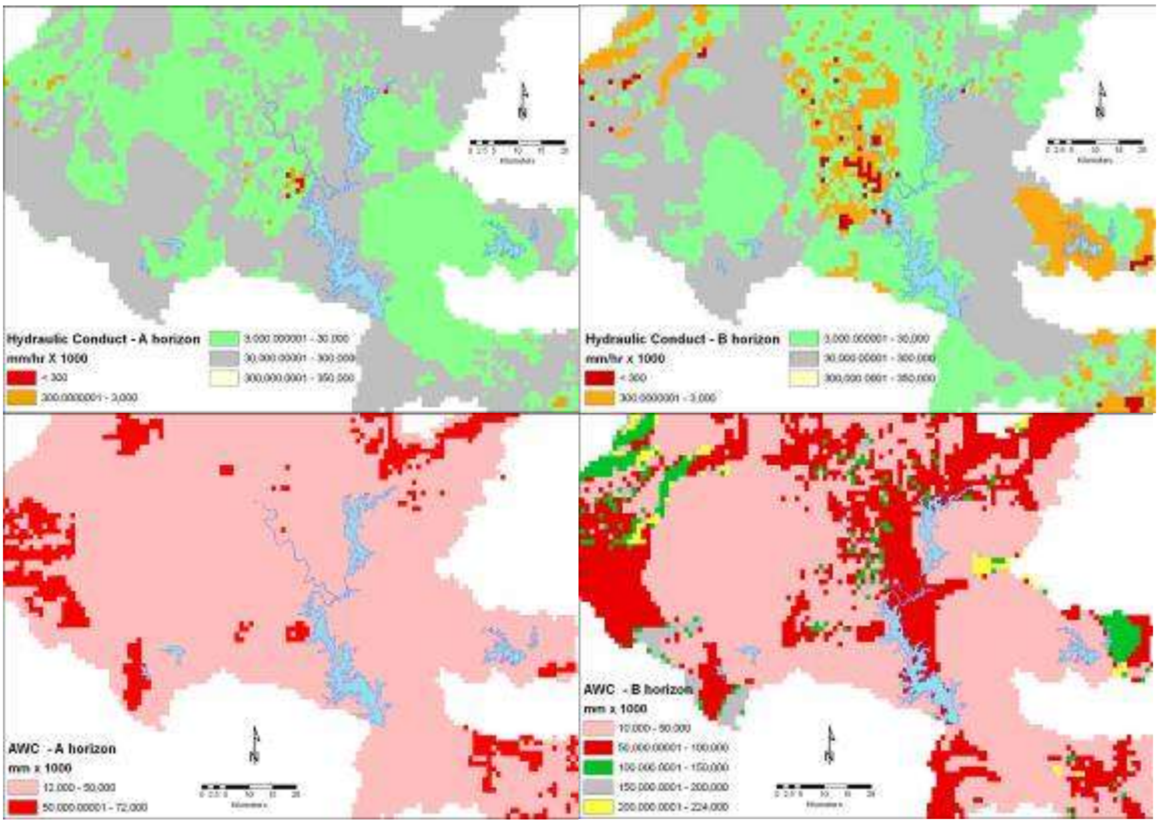

Figure 1: **Maps of the soil physical properties within the reservoir catchments (from NLWRA).**

Table 5: Modifications to soil properties of surface soil layer in water balance model due to three soil treatments.

Treatment	Layer depth	Ks (m day^{-1})	θ_s ($m^3 m^{-3}$)	θ_{FC} ($m^3 m^{-3}$)	θ_{PWP} ($m^3 m^{-3}$)	So (m $day^{-1/2}$)
Not treated	0.1	A horizon	A horizon	A horizon	A horizon	A horizon
Compacted	0.1	0.001	-0.08	-0.05	+0.03	÷10
Salinised	0.1	0.001	-0.08	-0.05	+0.1	÷10
Waxed	0.05	0.0001	A horizon	A horizon	A horizon	÷100

For the swale treatment the swales were introduced on a contour line with a width of swale of *Ds* and spacing between successive swales of *L*. This again can be modelled using the a 1D water balance model but modified to allow the up-slope infiltration from the natural soil to flow down and collect in the swale. This means that the water input for the swale (*Ps*) is now given by:

$$Ps = P + SRo.Ds(L / Ds - 1) \quad \text{Equation 2}$$

To express the runoff from the swale (*SRos*) in terms equivalent to that for the normal soil we must make the following calculation:

$$SRo = SRo_s.Ds / L \quad \text{Equation 3}$$

All water balance component values will be expressed as areal averages i.e. across the whole hill slope, not just for the swale area. For the swales we consider values of *L* (spacing) of 20, 40, and 80m and width of the swale of 2m. The ratio of area covered by swales is 10, 5 and 2.5% of the land surface for this spacing and width of swales. The swale can intercept water during runoff from the upslope area and this is taken into account when calculating the infiltration into the swale. In this simple analysis we do not consider cascading of runoff down a slope sequence as this is beyond the scope of this study. The modifications to the soil properties are given in Table 6 below. Surface runoff can still occur in the swale treatments as surface runoff is induced by either the precipitation (*Ps*) being greater that the soil infiltration rate (how fast water can enter the soil) or the storage capacity (how much water can fit in the soil profile) of the soil.

Table 6: Modifications to A horizon soil properties of swales in water balance model.

Treatment	Ks (m day^{-1})	θ_s ($m^3 m^{-3}$)	θ_{FC} ($m^3 m^{-3}$)	θ_{PWP} ($m^3 m^{-3}$)	So (m $day^{-1/2}$)
Swale bare	10 x soil	soil	soil	soil	3 x soil
Swale treed	100 x soil	+0.08	+0.05	soil	10 x soil

The model was run with the initial water content of all layers set to their field capacity. Field capacity is defined as the water content held in soil after excess water has drained away. This may result in a small overestimation of *RO* initially but since the model was run for 10 years this overestimation is negligible. The climate data for 10 years from 1997 to 2007 (SILO database (Jeffrey *et al.*, 2001)) were used in the modeling, and consisted of potential evaporation using the FAO56 method (Allen *et al.*, 1998) and rainfall. For the inter-swale region, where a grass crop was assumed to be the surface cover, a crop factor of 0.7 was used to multiply the potential evaporation to give potential evapotranspiration. For the swales a crop factor of 1 was used for the treed treatment.

For the three surface modification treatments and the bare swale treatment we consider that transpiration no longer occurs as plants are removed from the land surface. Modifying the A horizon properties of the soil will also affect the evaporation by changing the depth to which the drying front can penetrate in the soil. This reduction in Et will change the $\triangle S$ and D terms in the water balance.

5. DESKTOP ANALYSIS RESULTS

5.1. Surface Modification Treatments

Maps of suitable area as defined by GIS analysis for each treatment type are shown in Figures 2 to 4. It must be noted here that these maps are indicative of the type of area available for different techniques. Data sets used are the latest available but interpretation was not taken down to the property level because of sensitivities associated with individual properties being identified for treatment. Much more detailed data sets and ground truthing are required for increased confidence.

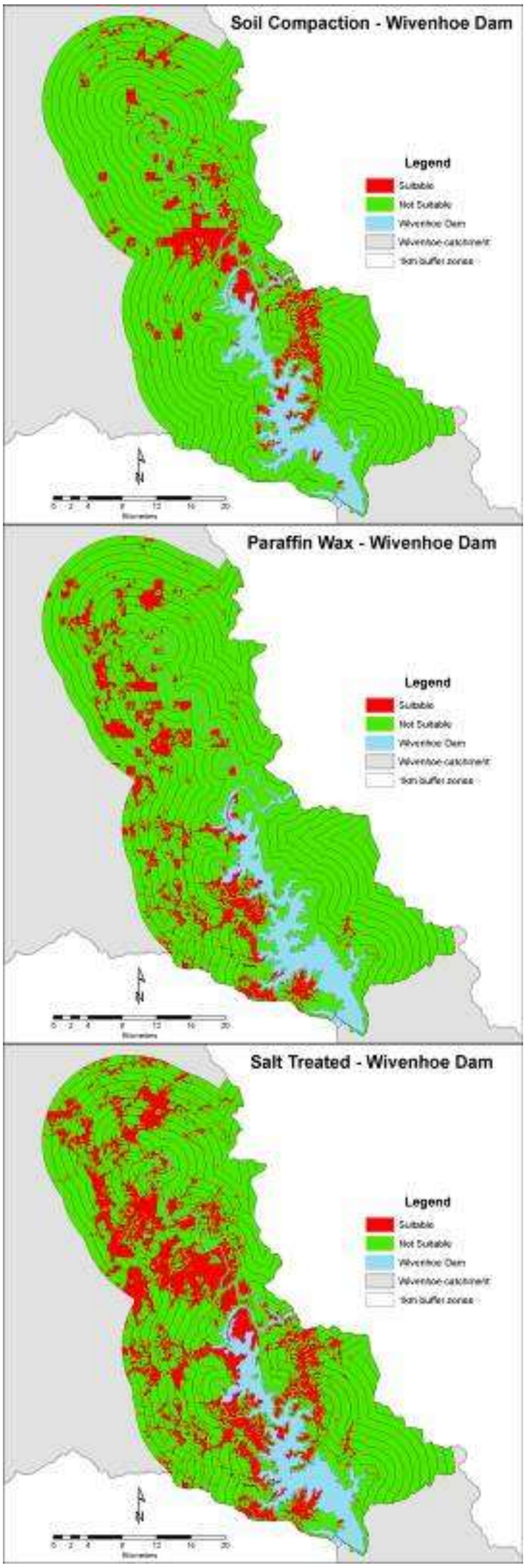

Figure 2: **Map showing location of areas suitable for runoff enhancement using surface compaction and wax and salt treatments in the Wivenhoe Dam catchment. 1km buffer zones are shown for a distance of 10 km from the storage.**

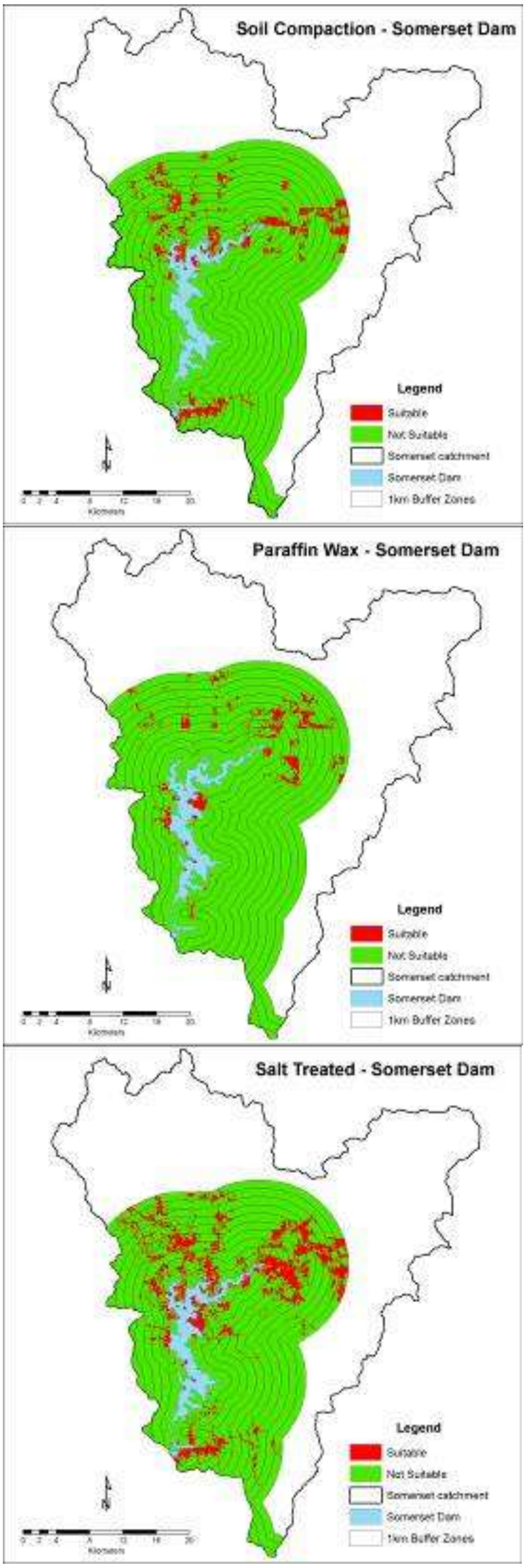

Figure 3: Map showing location of areas suitable for runoff enhancement using surface compaction and wax and salt treatments in the Somerset Dam catchment. 1km buffer zones are shown for a distance of 10 km from the storage.

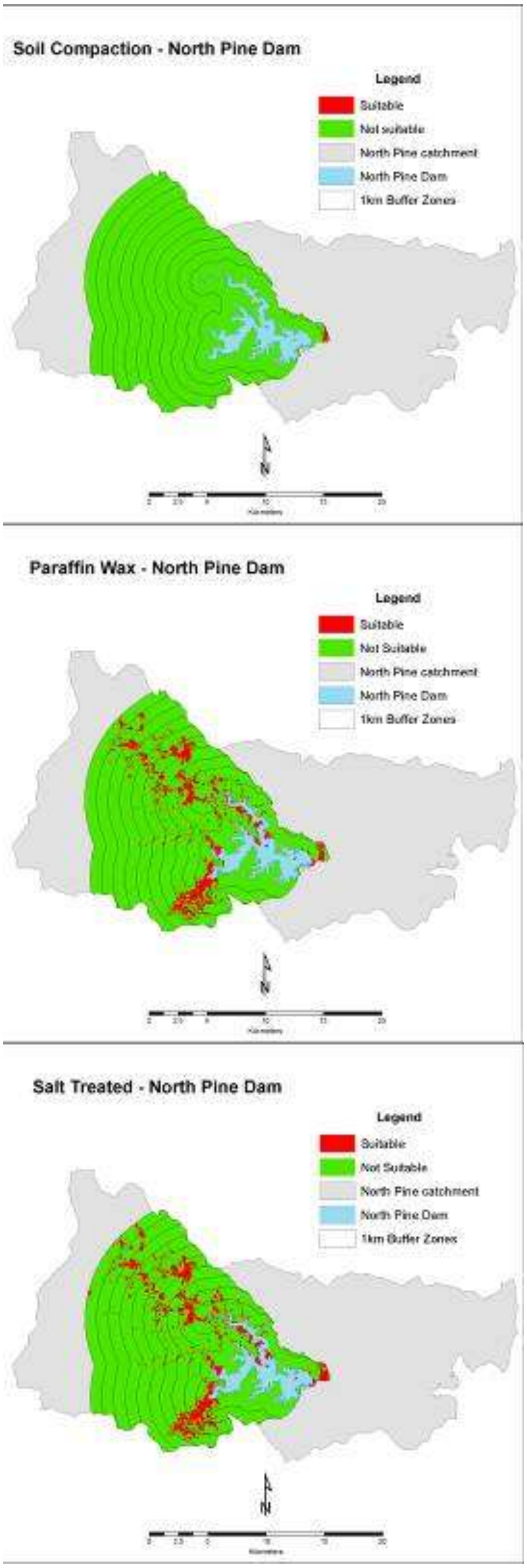

Figure 4: **Map showing location of areas suitable for runoff enhancement using surface compaction and wax and salt treatments in the North Pine Dam catchment. 1km buffer zones are shown for a distance of 10 km from the storage.**

The effects that surface treatments can have on runoff are illustrated in Figure 5 using soil type 1 as an example. All treatments show marked increases in *RO* relative to the normal untreated soil. In the normal and all treatments the dominant component of *RO* is surface runoff. For this soil the modelling indicates that the waxed treatment gave the largest increase in *RO*, with both an increase in *SRo* and *D*. The increase in *RO* is due the decrease in *Et* with the lowest value occurring in the waxed treatment.

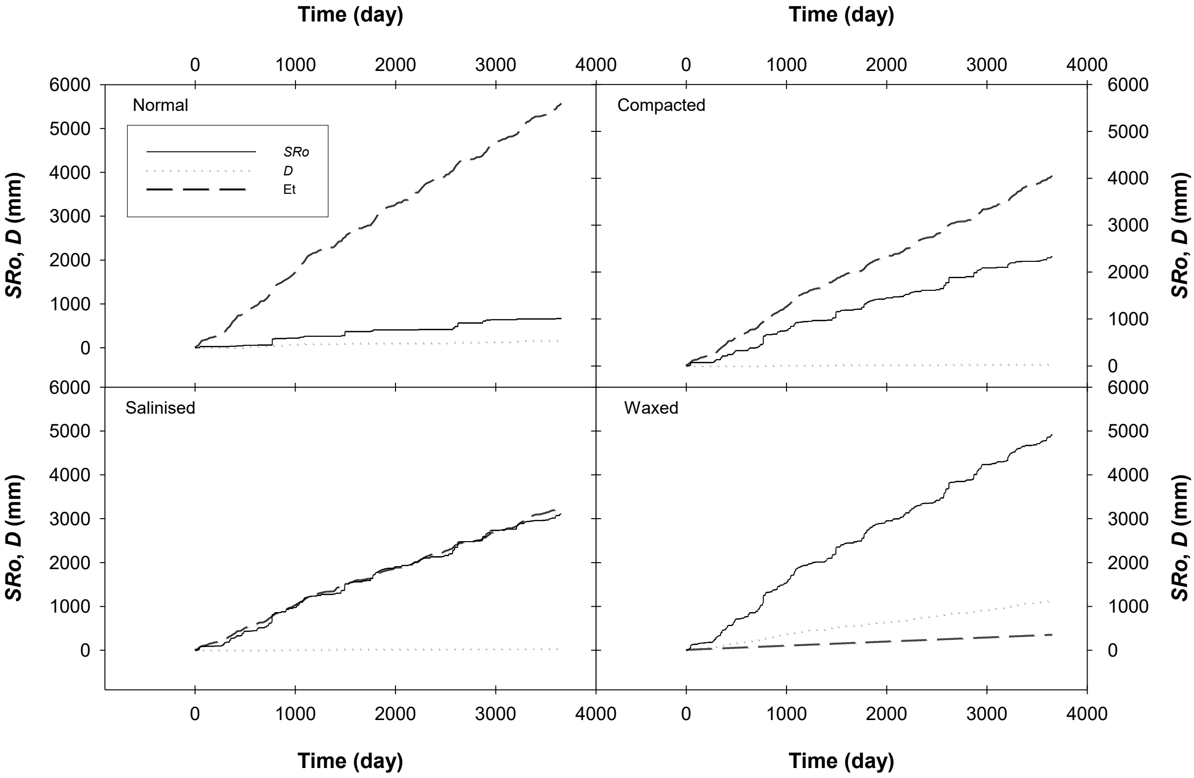

Figure 5: Comparisons of *SRo*, *D* and *Et* for treatments.

Average annual evapotranspiration, surface runoff and drainage for each soil type for treated and untreated conditions are shown in

Table 7. From this table it can be seen that the waxed treatment reduces evapotranspiration the most, resulting in the biggest increases in surface runoff and drainage. For many of the soils the results are the same, due to the processes in this climate being dominated by the soil water storage properties. The compacted and salt treatments are predicted to reduce the drainage from the soils compared to the normal soil, whereas the waxed soil is predicted to enhance drainage. This is due to the thinner surface layer used in the waxed treatment which greatly reduces evapotranspiration. It should be noted that in our analysis we assume that all water is either delivered to the storage or lost to evaporation; we do not account for any losses to major aquifer systems. Slight differences in total *SRo*, *D* and *Et* for each soil type are due to changes in soil moisture storage.

The waxed treatment is shown to have the greatest potential to increase runoff into the reservoirs. The increased runoff potential is expressed below in terms of average increase in runoff per year (Table 8). The range in percentage increase in runoff is 131 – 1710%, 238 – 2370% and 492 – 4541% for compaction and salt and wax treatments respectively.

Table 7: **Modelled average annual evapotranspiration (*Et*), surface runoff (*SRo*) and drainage (*D*) from the 14 soils (in mm), for each treatment, for a 10 year period.**

	Normal			Compaction			Wax treatment			Salt treatment		
Soil No.	*Et*	*SRo*	*D*	*Et*	*SRo*	*D*	*Et*	*SRo*	*D*	*Et*	*SRo*	*D*
1	561	67	17	405	233	3	35	492	113	326	311	4
2	561	67	17	405	233	3	35	492	113	326	311	4
3	561	67	17	405	233	3	35	492	113	326	311	4
4	561	67	17	405	233	3	35	492	113	326	311	4
5	581	67	0.4	405	233	3	35	492	113	326	311	4
6	574	67	0.4	405	233	3	35	492	113	326	311	4
7	586	67	0.4	405	233	3	35	492	113	326	311	4
8	586	67	0.4	405	233	3	35	492	113	326	311	4
9	586	67	0.4	405	233	3	35	492	113	326	311	4
10	560	67	17	470	127	45	203	352	85	386	150	105
11	560	67	17	470	127	45	203	352	85	386	150	105
12	581	67	0.4	470	127	45	203	352	85	386	149	105
13	581	67	0.4	470	127	45	203	352	85	386	149	105
14	635	14	3	569	44	31	177	290	173	524	58	61

Table 8: **Extra runoff (in mm) produced from different surface treatments from the 14 soils compared to untreated conditions. The percentage increase is shown in brackets.**

Soil No.	Compaction	Salt treatment	Wax treatment
1	152 (182%)	231 (276%)	521 (624%)
2	152 (182%)	231 (276%)	521 (624%)
3	152 (182%)	231 (276%)	521 (624%)
4	152 (182%)	231 (276%)	521 (624%)
5	169 (252%)	247 (369%)	538 (802%)
6	169 (252%)	247 (369%)	538 (802%)
7	169 (252%)	247 (369%)	538 (802%)
8	169 (252%)	247 (369%)	538 (802%)
9	169 (252%)	247 (369%)	538 802%)
10	88 (105%)	171 (204%)	354 (422%)
11	88 (105%)	171 (204%)	354 (422%)
12	104 (154%)	187 (278%)	370 (548%)
13	104 (154%)	187 (278%)	370 (548%)
14	58 (341%)	102 (600%)	446 (2628%)

The results presented so far have dealt only with the potential for different techniques to provide extra runoff, however a better measure of the suitability of a technique will be the cost of the water that it produces. Based on GIS analysis to identify areas suitable for each treatment, water balance modelling results, application costs for different treatments (Table 3) and land costs, it is possible to calculate the cost of the extra water that could be supplied by different surface treatments. This information is presented in Table 9 where the area available for treatment, the average annual runoff produced and cost of the water produced are summarised for each treatment and storage across each 1km buffer zone.

Results (Table 9) show that the cheapest way to enhance runoff is through surface compaction. Across all buffer zones and catchments the average cost of water produced was $0.48/kL, this is approximately 70% of the cost of water produced through wax treatment ($0.71/kL) and about three times cheaper than salt treatment ($1.48/kL). It is also worth noting that the area of catchment available for surface compaction in the North Pine catchment was very small therefore this technique is not applicable there.

Table 9: Area available for treatment (*A*, in km2), extra average annual runoff produced (*RO*, in ML) and cost ($/kL) of each treatment type in each storage for different buffer widths. Costs are calculated based on the pricing in Table 3 and land cost of $7,000/ha written off over 40 years.

		Surface compaction			Wax treatment			Salt treatment		
Buffer zone	**Model results**	**Wivenhoe**	**Somerset**	**North Pine**	**Wivenhoe**	**Somerset**	**North Pine**	**Wivenhoe**	**Somerset**	**North Pine**
0-1 km	A - km^2	52.5	16.6	0.0	38.1	30.6	8.5	98.2	30.6	8.5
	RO - ML	5711	1849	0	14694	12467	4411	18715	7501	1953
	Cost - $/kL	**0.51**	**0.50**	-	**0.84**	**0.80**	**0.63**	**1.78**	**1.38**	**1.47**
1-2 km	A - km^2	20.2	5.5	0.4	17.7	12.5	3.9	43.0	12.5	4.5
	RO - ML	2599	659	58	7237	5313	2053	8772	3041	1030
	Cost - $/kL	**0.43**	**0.46**	**0.38**	**0.79**	**0.76**	**0.62**	**1.66**	**1.39**	**1.48**
2-3 km	A - km^2	15.1	4.5	0.0	14.2	10.8	2.7	32.0	10.8	2.9
	RO - ML	1898	435	<1	6489	4752	1399	6680	2637	673
	Cost - $/kL	**0.44**	**0.57**	**-**	**0.69**	**0.71**	**0.60**	**1.62**	**1.39**	**1.46**
3-4 km	A - km^2	10.6	4.4	0.0	14.4	10.6	3.3	27.7	10.6	3.3
	RO - ML	1313	628	<1	6689	4700	1699	5806	2580	815
	Cost - $/kL	**0.45**	**0.39**	**-**	**0.71**	**0.74**	**0.63**	**1.61**	**1.39**	**1.37**
4-5 km	A - km^2	9.5	5.2	0.0	15.7	10.7	2.7	30.1	10.7	2.7
	RO - ML	1188	422	0	7115	4297	1387	6252	2639	759
	Cost - $/kL	**0.44**	**0.68**	**-**	**0.70**	**0.73**	**0.63**	**1.63**	**1.37**	**1.20**
5-6 km	A - km^2	7.5	3.9	0.0	16.2	8.9	1.3	29.7	8.9	1.3
	RO - ML	1039	360	<1	7663	3521	677	6456	2180	306
	Cost - $/kL	**0.40**	**0.60**	-	**0.69**	**0.82**	**0.62**	**1.56**	**1.38**	**1.44**
6-7 km	A - km^2	6.0	3.7	0.0	11.7	8.5	1.2	23.1	8.5	1.2
	RO - ML	906	357	0	5450	3582	618	5038	2074	281
	Cost - $/kL	**0.37**	**0.58**	**-**	**0.70**	**0.77**	**0.63**	**1.55**	**1.39**	**1.45**
7-8 km	A - km^2	2.9	3.3	0.0	11.6	6.3	1.0	18.6	6.3	1.1
	RO - ML	412	485	0	5442	2633	526	4061	1530	250
	Cost - $/kL	**0.39**	**0.38**	**-**	**0.69**	**0.78**	**0.62**	**1.55**	**1.39**	**1.49**
8-9 km	A - km^2	4.6	3.7	0.0	8.1	7.4	1.0	17.1	7.4	1.1
	RO - ML	701	452	2	3641	3068	517	3796	1807	251
	Cost - $/kL	**0.36**	**0.45**	**0.69**	**0.72**	**0.78**	**0.63**	**1.52**	**1.39**	**1.48**
9-10 km	A - km^2	4.3	4.2	0.0	8.2	9.3	0.6	16.3	9.3	1.0
	RO - ML	563	268	<1	3566	3829	338	3392	2282	230
	Cost - $/kL	**0.42**	**0.87**	**0.44**	**0.75**	**0.79**	**0.58**	**1.63**	**1.38**	**1.47**

Of all the scenarios tested, it appears surface compaction in the Wivenhoe and Somerset catchments is most attractive. While the analysis zone extends to a distance of 10km from the storages it is probably best to limit this distance so as to minimise extra costs involved in channelling water to the storages and to minimise losses during transport. If we assume a maximum distance from storage of 4km we can assess the amount and cost of water that could be delivered to Wivenhoe and Somerset dams through surface compaction as is shown in Table 10.

To enable a comparison of the relative costs of different water supply strategies we have also compared costs to the desalination plant being built at the Gold Coast which aims to produce 45,600 ML/year. SEQWater estimates that the cost to produce this water (without delivery) is between $1.20 and $1.50/kL (http://www.waterforever.com.au/_uploads/67_Desalination.pdf). It should be noted, however, that the costs calculated for runoff enhancement do not include treatment costs whereas the desalination costs do. It is also worth noting that the extra yield from the storages will be less than the extra runoff produced through surface treatment due to evaporative losses.

Table 10 shows that there is the potential in the Wivenhoe and Somerset catchments to produce 15092 ML of water per year for around $0.47/kL. This is less than half of the volume that can be produced by the Gold Coast desalination plant and around 4% of 430,000 ML of water delivered to south-east Queensland on an annual basis (SEQWater 2005 figures). The downside of this scale of production through surface treatment is the area required to provide the water. The results we present in Table 10 would require a land area of nearly 130 km2; this is likely to be a major impediment to the uptake of this technique.

Table 10: Volume and cost of water produced from compaction treatment in the Wivenhoe and Somerset catchments. Results are compared to costs estimated for production of water through desalination using estimates for the Gold Coast plant. N.B. Costs calculated for runoff enhancement do not include treatment costs or losses of extra water produced through evaporation.

	Water produced (ML/y)			
Zone of treatment	**Wivenhoe**	**Somerset**	**Combined**	**Cost of water ($/kL)**
0 – 1 km	5711	1849	7560	$0.50/kL
0 – 2 km	8310	2508	10818	$0.48/kL
0 – 3 km	10208	2943	13151	$0.49/kL
0 – 4 km	11521	3571	15092	$0.47/kL
Desalination			45600	$1.20-$1.50 / kL

5.2. Swale Treatments

The swale treatments show an increase in the amount of the drainage component (flow to groundwater) of the runoff for all soils in the bare swale treatments but no changes for the treed swales (Table 11). Overall the runoff (drainage plus surface runoff) is slightly reduced for the treed swale treatment compared with the normal soil, while the bare swales show a small increase in runoff for all soils (Table 12). The reason for the small changes to runoff for the treed swales is related to a combination of the rainfall characteristics for the study period and the increased transpiration losses. For the ten year study period used, a large proportion of the rainfall events (85%) were less than 10mm (Figure 7) and, therefore, generated very little surface runoff. Under such circumstances the increase in infiltration is largely cancelled by increased transpiration losses.

Table 11: Modelled average annual drainage (*D*) from the 14 soils (in mm), for each treatment, for a 10 year period in the swale modelling. Values are areal averages not swale specific values.

Soil No.	Normal	Bare swale			Treed swale		
		L = 20 m	L = 40 m	L = 80 m	L = 20 m	L = 40 m	L = 80 m
	D (mm)	D (mm)	D (mm)	D (mm)	D (mm)	D (mm)	D (mm)
1	17	23	20	18	17	17	17
2	17	23	20	18	17	17	17
3	17	23	20	18	17	17	17
4	17	23	20	18	17	17	17
5	0.4	8	4	2	0.4	0.4	0.4
6	0.4	8	4	2	0.4	0.4	0.4
7	0.4	8	4	2	0.4	0.4	0.4
8	0.4	8	4	2	0.4	0.4	0.4
9	0.4	8	4	2	0.4	0.4	0.4
10	17	23	20	18	17	17	17
11	17	23	20	18	17	17	17
12	0.4	8	4	2	0.4	0.4	0.4
13	0.4	8	4	2	0.4	0.4	0.4
14	3	0.7	5	4	3	3	3

Table 12: Change in average annual runoff (mm) produced from different swale treatments from the 14 soils compared to untreated conditions. The percentage change is shown in brackets.

Soil No.	Bare Swale			Treed Swale		
	L = 20 m	L = 40 m	L = 80 m	L = 20 m	L = 40 m	L = 80 m
1	6 (7%)	3 (3%)	1 (2%)	-5 (-6%)	-2 (-3%)	-1 (-1%)
2	6(7%)	3(3%)	1(2%)	-5 (-6%)	-2 (-3%)	-1 (-1%)
3	6(7%)	3(3%)	1(2%)	-5 (-6%)	-2 (-3%)	-1 (-1%)
4	6(7%)	3(3%)	1(2%)	-5 (-6%)	-2 (-3%)	-1 (-1%)
5	7 (11%)	4 (6%)	2 (3%)	-5 (-7%)	-2 (-4%)	-1 (-2%)
6	7 (11%)	4 (6%)	2 (3%)	-5 (-7%)	-2 (-4%)	-1 (-2%)
7	7(11%)	4(6%)	2(3%)	-5 (-7%)	-2 (-4%)	-1 (-2%)
8	7(11%)	4(6%)	2(3%)	-5 (-7%)	-2 (-4%)	-1 (-2%)
9	7(11%)	4(6%)	2(3%)	-5 (-7%)	-2 (-4%)	-1 (-2%)
10	6 (7%)	3 (3%)	1 (2%)	-5 (-6%)	-2 (-3%)	-1 (-1%)
11	6 (7%)	3 (3%)	1 (2%)	-5 (-6%)	-2 (-3%)	-1 (-1%)
12	7 (11%)	4 (5%)	2 (3%)	-5 (-7%)	-2 (-4%)	-1 (-2%)
13	7 (11%)	4 (5%)	2 (3%)	-5 (-7%)	-2 (-4%)	-1 (-2%)
14	4 (24%)	2 (24%)	1 (6%)	-1 (-6%)	-1 (-3%)	0 (-2%)

Table 13 shows the modelled average annual evapotranspiration (*Et*), surface runoff (*SRo*) and drainage (*D*) using Soil 5 as an example. The surface runoff (*SRo*) is very similar for the normal and swale treatments but *Et* and *D* varied. The only treatment where drainage (*D*) has increased is the bare swale treatment. There was a reduction in the amount of drainage as the spacing (*L*) of bare swales increased. In this modelling exercise *SRo* was not reduced as much as expected and the reason for this was found to be the occurrence of a small number of extremely high rainfall events that exceeded the infiltration capacity of swale soils and over-topped the storage capacity of the swales. Much of the surface runoff predicted is the result of three days where rainfall exceeded 90mm.

The biggest predicted increase in annual runoff is 7mm/ha/yr for the bare swale treatment with a spacing of 20m (Table 12). This is equivalent to 70kL/ha/yr and with a cost of $2,400/ha/yr would result in very expensive water at approximately $30.00/kL. To produce the same amount of water as the runoff enhancement treatments for the zone with 4 km of the reservoir boundary (15092 ML or 4% of SEQ supply) approximately 189,000 ha (1890 km2) would have to be utilised for swale treatments spaced at 20m. While this total area of treatment is more than that for the runoff enhancement methods (130 km2) it should be noted that only 10% (189 km2) is taken out of production as land use continues uninterrupted in the inter-swale area. The cost for water produced is the same for all bare swale scenarios the only difference is the area of land required to be treated.

Table 13: Modelled average annual evapotranspiration (*Et*), surface runoff (*SRo*) and drainage (*D*) from Soil No. 5 (in mm), for a 10 year period. Note that the reason the treed swales have a greater total water use is that the soil/rooting depth is assumed to be deeper and the difference is the water extracted from the initial profile at field capacity.

	Et	*SRo*	*D*
Normal	581	67	0.4
Bare Swale L = 20 m	573	66	8
Bare Swale L = 40 m	577	66	4
Bare Swale L = 80 m	579	67	2
Treed Swale L = 20 m	587	62	0.4
Treed Swale L = 40 m	584	64	0.4
Treed Swale L = 80 m	583	65	0.4

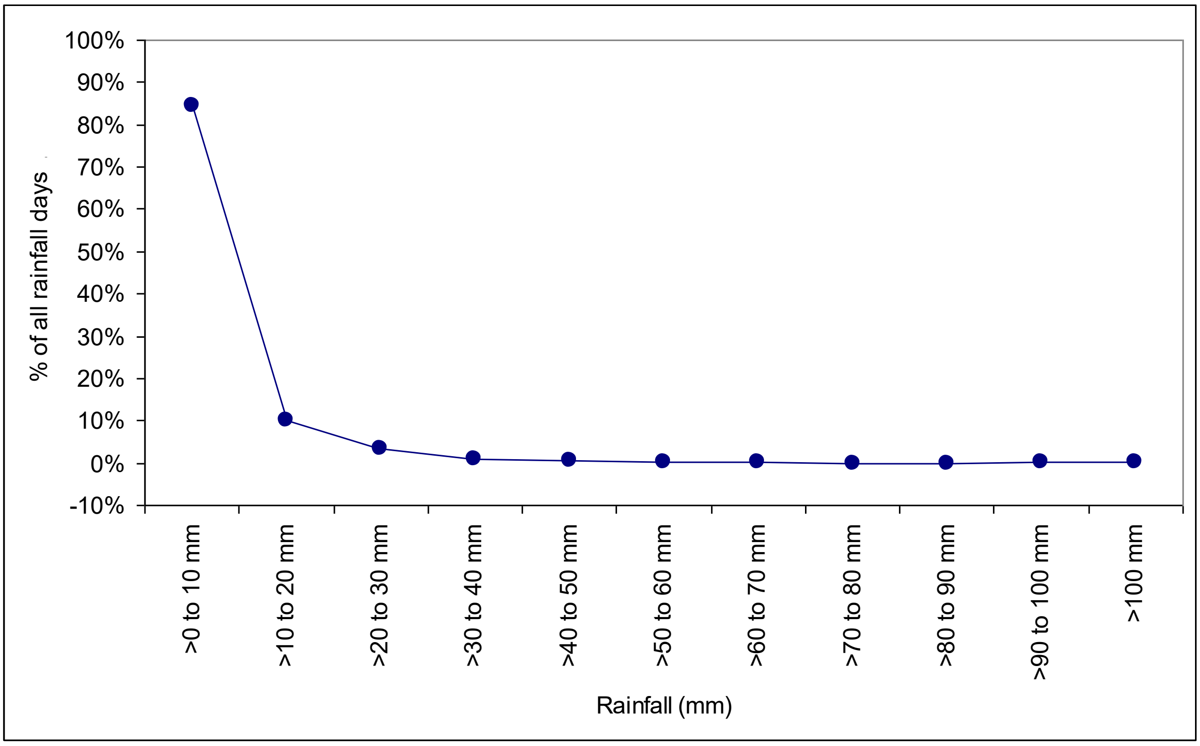

Figure 6: Rainfall frequency analysis for the 10 year study period. Rainfall is dominated by rainfall events with less than 10mm of daily rainfall.

6. POTENTIAL EFFECTS ON STORAGE WATER QUALITY

The biggest potential impact on water quality from runoff enhancement techniques considered in this report is the delivery of extra sediment through erosion. Myers (1975) states that if water from water harvesting systems is for human consumption then it is likely that additional filtration and treatment will be needed. With an increase in the proportion of water delivered over the surface of the land, rather than through the soil, the time to delivery of water will be much quicker. As a result of this increased speed of transport the erosive power of the water increases. While this is seen as a drawback of such techniques there are methods that can be used to prevent sediment loss or remove it as it travels down the hill slope. Such methods could include installation of small wetlands or settling ponds, or utilisation of vegetation buffer strips (Hairsine *et al.*, 2007). The speed of water delivery may also have important consequences for dam safety, particularly guidelines for flood releases.

The other potential water quality impact comes from the breakdown of the treatment products themselves. This is not seen as an issue for compacted soil. For paraffin waxes the effects are also seen as being minimal. Paraffin waxes are approved for human consumption therefore contamination of runoff water is unlikely to be an issue (Richardson *et al.*, 2004). Short term studies of the sodium losses from salt treated hill slopes has shown no significant increases compared to control slopes (Frasier *et al.*, 1987), however it is likely that over a longer term salt treatments would eventually lead to increased water salinity.

The bare swales are unlikely to produce as much soil erosion as the surface treatments as the area of bare soil is much reduced. Runoff processes in the inter-swale area continue as they do at present and the only potential time soil erosion would be increased is when the capacity of the bare swales to intercept water is exceeded. For runoff events that can be contained by the swales, soil erosion is likely to be reduced. Maintaining a bare soil in the swale area is likely to require the use of some chemical sprays which could also impact on storage water quality.

7. SOCIAL IMPACTS

One of the social impacts of surface treatments and swales is likely to be related to the loss of visual amenity. Surface treatments usually require the removal of vegetation and implementation of engineering works which would result in the appearance of what could be termed ‘scars’ over large areas of the landscape. Other social impacts could result from the changing from grazing land to water harvesting land. There are two main ways in which broad scale water harvesting could be implemented in these catchments. Firstly, land could be purchased from landholders and the government would be responsible for surface treatments, or, secondly, water could be purchased from the land owners who are responsible for implementing and maintaining runoff enhancement treatment (such a scheme is described by Hairsine *et al.* (2007)). If land is purchased from owners then some farmers may leave the area resulting in local impacts to communities. If the water delivered from the farms is purchased from the farmers then a new, potentially greater, income stream could be developed.

8. SUGGESTIONS FOR FURTHER RESEARCH

Runoff and infiltration enhancement techniques definitely show potential for increasing water supply to the major storages in SEQ, however the area to be treated would have to be very large; a factor which is likely to prevent adoption. For swales the cost of extra water produced ($30/kL) is also highly likely to be prohibitive. If such techniques are considered to be a viable option for supplementing water supplies in south-east Queensland then further research is required. The issues that will need to be addressed include:

1. Increasing model confidence is the first requirement. The existing modelling is based on coarse resolution soils data sets and assumptions regarding soil characteristics. Increasing model confidence would require field testing of techniques and collection of better soils data.

2. Field trials of actual applications on different soil types including assessments of water quality issues.
3. A more thorough assessment of social impacts. Social impacts are likely to be wide and varied and experts in this field need to be consulted.
4. For runoff enhancement, assessing issues of connectivity of suitable areas for treatment is essential as current modelling does not assess this. Connectivity of treatment areas is essential for minimising costs of networks to deliver water to storages and transmission losses.
5. For swales, assessing the connectivity of groundwater systems beneath the treatment slopes with systems that supply major storages.
6. Development of water pricing structures. Such structures would be necessary if land holders were to be paid for the water delivered from their property. Structures would need to include current income versus potential water harvesting income water pricing may increase and decrease with changes in water availability in the region.
7. Assessment of the impact of increased volume and, in the case of runoff enhancement, speed of water delivered to storages on dam safety. Current dam safety procedures may need to be modified in response to the faster delivery of water to the storages.
8. Assessment of the impacts of runoff or drainage enhancement on regional groundwater systems, particularly in areas within the catchments which rely on this resource.
9. Assessment of the effects of runoff enhancement on water quality and testing of means by which to reduce sediment loss.
10. Assessment of the potential environmental impacts that could result from implementation of surface treatments and swales.
11. Assessment of the effects of using climate data from a different period. We have used the last ten years in our modelling, however this is the climate that has resulted in the present low dam levels.

9. KEY MESSAGES

The main findings were:

- Surface treatments all offer a potential means by which to increase the volume of water delivered to the three major storages in south-east Queensland.
- Based on utilisation of all suitable areas within 4km of Wivenhoe and Somerset storages it is estimated that 15092 ML of water could be produced annually through runoff enhancement through surface compaction (4% of SEQ requirements).
- In terms of the costs of water provided, surface compaction is the best method with costs estimated to be $0.47/kL (excluding treatment costs and evaporative losses). Costs are competitive when compared to the estimated $1.20 - $1.50/kL estimated for water from the desalination plant on the Gold Coast (water production and treatment not delivery).
- Bare swales produced increases in drainage which result in extra water at a cost of $30.00/kL.
- The key water quality issue with regards to all surface treatments is the enhancement of sediment delivery due to increased surface runoff.
- The major drawback of surface treatment and swale techniques is the area of land required to produce significant extra runoff. For surface compaction 130 km2 of land is required to produce 4% of the water requirements of SEQ. For swales 189 km2 of land would need to be taken out of production to produce this same volume.
- The large areas of land required for such techniques would have major social and environmental impacts which would require careful consideration.

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