Water SA 50(3) 246–252 / Jul 2024
https://doi.org/10.17159/wsa/2024.v50.i3.4121

Research paper

Estimating the cost-effectiveness of several reservoir evaporation suppression strategies: a case study

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Reservoirs often experience significant evaporation, causing a reduction in productive water use and prompting calls to curtail the loss. While efforts to reduce evaporation have predominantly focused on improving efficiencies, there has been a comparatively limited exploration of the associated costs per unit of additional water yield. To address this, a unit reference value (URV) calculation approach was employed in a case study to compare the unit costs of this additional yield through various evaporation suppression methods. The evaluated techniques included chemical monolayers, shade cloth, and both hard and soft floating covers. The URV calculation factored in capital, operating, and maintenance costs over a 20-year term, specified water-saving efficiencies for each technology, and various environmentally driven evaporation and social discount rates. The resulting URVs were compared with those for raising the Clanwilliam Dam, a large-scale groundwater scheme and the URVs for desalination. Notably, monolayers emerged with the lowest URV, but their yield efficiency is severely compromised by their short lifespan and high susceptibility to wind. The URVs of shade cloth proved competitive with those of desalination but are practical only for relatively small areas. In contrast, floating hard and soft covers demonstrated higher per-unit water delivery costs than desalination due to more frequent capital equipment replacements caused by their faster wear and weathering. The findings suggest that current evaporation suppression technologies may be economically unfeasible for agricultural and even domestic water supplies. The URV calculation serves as a valuable tool for comparing the cost-effectiveness of diverse yield-additive strategies.

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DATES
Received: 30 January 2024
Accepted: 17 July 2024

KEYWORDS
evaporation suppression
cost-effectiveness
unit reference value
URV
levelised cost

INTRODUCTION

Evaporation losses can be a significant proportion of total agricultural reservoir storage in arid and semi-arid climates, limiting local economic activity (Martínez-Granados et al., 2011). For instance, approximately 40% of storage capacity is lost from on-farm reservoirs in Queensland, Australia (Craig et al., 2005), causing 375 million USD worth of foregone agricultural production (Martínez Alvarez et al., 2008). Gökbulak and Özhan (2006) calculated that more water is lost annually to evaporation than is used for domestic and industrial purposes from 129 lakes and 223 reservoirs in Turkey, equivalent to >20% of irrigation water requirements, while annual evaporation from farm storage in the Segura catchment, Spain, represents more than 8% of local irrigation requirements (Martínez Alvarez et al., 2008).

In South Africa, evaporation from open water surfaces ranges from 1 400 to 3 000 mm/a (Schulze et al., 2007), representing 14 000 to 30 000 m^3/ha of non-beneficial use of water annually. Concerns over evaporation from storage are accentuated during times of drought. During the severe 2015–2017 drought that affected the City of Cape Town, government and public calls were made to invest in evaporation suppression measures (Meiring, 2017; RSA, 2019). Substantial research has been undertaken into the physics and mechanisms of evaporation suppression, but relatively little work has been done on the cost-effectiveness of suppression. Here we compare the cost-effectiveness of several technologies using a standardised method for assessing the different capital, operational, and life cycle costs. Using a case study, we provide a sensitivity analysis with high and low evaporation rate ranges, as well as varied discounting rates, to cover the full ranges of likely annual cost drivers of suppression.

Background

Research into evaporation suppression technologies dates to the early 1900s, which includes the use of physical (Lehmann et al., 2019) and chemical barrier films (Barnes, 2008). The use of suspended covers such as roofs to suppress evaporation is described as early as the 1950s (Beadle and Cruse, 1957; Magin and Randall, 1960).

Craig et al. (2005) suggest that high evaporation reductions are possible by applying physical covers to small agricultural reservoirs (typically < 10 ha). Covers may be suspended (Gallego-Elvira et al., 2011) or floating (Aminzadeh et al., 2018; Cooley, 1970; Lehmann et al., 2019). Suspended covers require the use of monofilament shade cloth held by high-tension cables that are anchored into the embankment. The structure (cables and anchors) has a design life of about 30 years and the shade cloth itself about 15 years (Craig, 2005).

Assouline et al. (2011) suggest that floating covers reduce losses more than suspended barriers but are affected by wind as well as changing water levels and splash (Craig et al., 2005). Floating hard and soft covers act as an impermeable barrier between a water body and the overlying air. Hard floating covers are usually modular plastic elements that are manufactured in the shape of discs or balls, with a lifespan of 12+ years, and are suitable for smaller reservoirs (<0.1 km^2) (Lehmann et al., 2019). However, higher wind speeds cause modular floating barriers to pile up, reducing suppression efficiency (Lehmann et al., 2019).

Floating soft covers, typically polyethylene plastic sheeting, may produce high levels of evaporation suppression while allowing for splash-over, maintenance access, and water oxygenation. A soft-cover polyethylene layer typically contains its buoyancy cells and may be white above to reflect some insolation and dark beneath to reduce light transmission through the sheeting. With a floating sheet, water may lie on top of parts of the mat and is available for evaporation. The sheeting can be damaged by animals, strong winds, waves, and solar weathering, thus limiting its lifespan to 7–10 years (Southern Cape Landowners Initiative, 2018).

Chemical barrier films offer options for saving water but can be less effective than physical barriers (Craig et al., 2005). Chemical films are formed at the air/water interface or phase boundary (Barnes and Gentle, 2011). When spread on the water, the monolayer self-assembles to form a thin (one molecule thick) layer of long-chain fatty acids–cetyl/stearyl alcohols (Barnes, 2008; McJannet et al., 2008). Rideal (1925) presented the first recorded demonstration that monolayer films could reduce evaporation rates although investigations into the method began earlier (Langmuir, 1917). Research in the 1940s and 50s demonstrated their potential for evaporation suppression (Archer and LaMer, 1954; Langmuir and Schaefer, 1943).

Despite demonstrable effects on evaporation rates in favourable conditions, the application of monolayer films (particularly on larger storages) is no longer widely practiced (Barnes, 2008), though there has been some renewed interest (Brink et al., 2011). Problems include contaminants introduced in the manufacturing process, volatilisation of the film material, displacement by wind, and decomposition in the environment (Barnes, 2008). Displacement by wind is particularly problematic, with most field trials demonstrating large losses of efficiency with wind speeds greater than 8 km/h (Karimzadeh et al., 2023; Barnes, 2008; Fitzgerald and Vines, 1963; Vines, 1962). The life span of the monolayer is 2–3 days and the product needs constant re-application. An advantage of a shorter lifespan is being able to limit the period of application to specific seasons and having low capital outlay.

METHODS

The core approach of this study was to estimate and compare the cost-effectiveness of additional water yield through using different evaporation suppression technologies under different evaporation scenarios, and by considering their different suppression efficiencies.

Study area

The research used a study site in the West Coast District Municipality, South Africa (Fig. 1), which consists of two farm dams (Avontuur and Buchu) located on the plateau area of Piketberg Mountain, Western Cape Province, South Africa (Fig. 1). Here, the irrigation water supply is limited to what can be captured as runoff from small catchments located nearby. Opportunities for augmentation of supply from other sources are limited because of the higher altitude of the study site. Conserving water locally and the effectiveness of use is therefore essential. The evaluation approach was to estimate the magnitude of evaporative losses from these two farm reservoirs and to compare the cost efficiencies of various barrier technologies for suppressing evaporation.

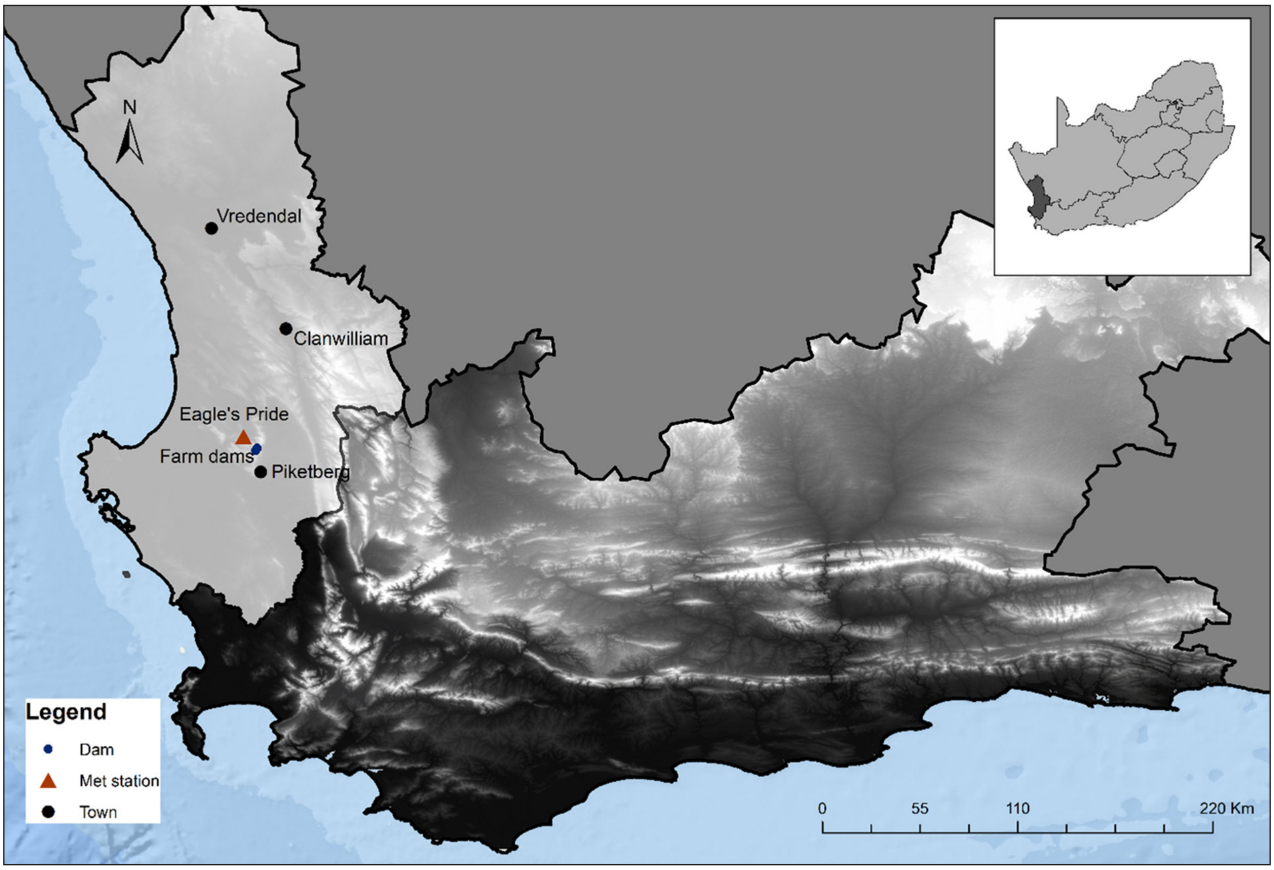

Figure 1. Location of study site of farm dams and micro-met station on Piketberg Mountain, South Africa

Estimation of losses from water storage

Two sources of evaporation data were used to estimate the range of evaporation levels in the study area. In the first, the Penman-Monteith (PM) potential evapotranspiration (Et_o) equation (Allen et al., 1998), modified for free and open water surfaces (Savage et al., 2017), was applied to hourly micrometeorological data obtained from a nearby automatic weather station. This is the Eagle's Pride Station belonging to the Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL) network (Muche et al., 2018) (Fig. 1). The instrument specifications are also given by Muche et al. (2018). The data were inspected for quality control purposes and data-logging errors were corrected. ET_o was automatically calculated as a SASSCAL data output but modified in this case by multiplying the result by 1.05 as recommended by Allen et al. (1998) for shallow (< 2–3 m depth) open water surfaces. The hourly values were aggregated to an annual value of the observed data.

The second source of evaporation data was obtained from nearby Symons pans at Misverstand Weir (Department of Water and Sanitation Station Number G1E008) and Withoogte Purification Works (G1E009). The mean annual pan evaporation value was modified by a pan-to-lake coefficient of 0.83 based on values published in Bailey and Pitman (2015). Given the various sources of evaporation data, a representative evaporation range could be established.

Calculating efficiencies of evaporation suppression technologies

Four evaporation suppression technologies were chosen for comparison – (i) a monolayer film, (ii) a shade cloth installation, (iii) a hard floating cover, and (iv) a soft floating flexible mat (Table 1). When the air is still, monolayers can reduce evaporation by up to 60% (Jones, 2018). However, in trials on large storages they are less effective – approximately 40% in wind conditions of less than 8 km/h, dropping to 10–20% if winds rise to 16 km/h, and 0% for winds > 24 km/h (Fitzgerald and Vines, 1963). Craig et al. (2005) estimate water savings from monolayer films applied to large-scale storage to be between 5% and 30%, depending on environmental conditions, with 15% being a medium efficiency scenario (Brink et al., 2011). For this study, an evaporation reduction of 20% is assumed, the region having relatively high mean daily wind speeds.

Shade cloth coverings reduce evaporation by 60–80% (Craig et al., 2006, 2005) and we assume an efficiency of 70%. Lehmann et al. (2019) and Aminzadeh et al. (2018) report that floating modular hard covers may reduce evaporation losses by between 70% and 80% while Craig (2005) and Craig et al. (2006) estimate efficiencies of between 85% and 95%. This evaluation uses an evaporation suppression efficiency of 80% for hard covers and 90% for soft covers. The monolayer suppression efficiency falls to 10–20% when wind speeds are between 8 and 16 km/h (Fitzgerald and Vines, 1963). The average daily wind speeds at Eagle's Pride on the Piketberg Mountain, and indeed for much of the Western Cape, South Africa, are often higher than this threshold, which strongly limits this technology's efficiency.

Pricing the interventions for evaporation suppression

We used pricing derived from market research and the literature to provide the costs of applying the various interventions. The cost estimates were taken from company and distributor websites, where prices per kg (monolayer film) and surface coverage (physical covers) are given. Estimated capital and operational costs for selected evaporation suppression technologies are reflected in Table 1 in 2017 US dollar (USD) values. The capital costs of purchase (Table 1) along with the annual operating and maintenance costs were evaluated over 20 years. Installation and transport costs were not included as these are site-dependent and highly variable. The floating soft covers/mats and hard covers were priced with capital replacements at 8 and 12 years, respectively, the more frequent capital replacement driven by the higher levels of weathering, degradation, and damage that occurs through wave action.

Comparing the cost-effectiveness of different interventions

We use the unit reference value (URV) to compare different evaporation suppression technologies in terms of the volume of additional yield generated by each method. The URV is an assessment used in South Africa to develop economic appraisals of different water resource projects (Joubert et al., 2003; Van Niekerk and Du Plessis, 2013). The use of this method has expanded in more recent times to include assessments of clearing invasive alien plants, desalination, water demand management, and various aspects of environmental management (Bester et al., 2020). In essence, the URV is a financial calculation similar to the levelised cost of electricity (LCOE) calculations that are used for financial comparisons of alternative supply options in the electricity sector (Raikar and Adamson, 2019). Both are economic measures for comparing lifetime costs across different production technologies which have unequal life spans, different project sizes, capacities, and capital, operational and maintenance costs (Raikar and Adamson, 2019). The assessment offered here is comparable to Bester et al.(2020)'s URV1 interpretation.

The URV as given by Van Niekerk and Du Plessis (2013) is calculated by:

$$\text{URV} = \frac{\text{Present Value (PV) of life cycle costs}}{\text{PV of quantity of water supplied}}$$

where: PV of life cycle costs = PV of capital costs + PV of O&M costs over a specified term.

Capital costs can include purchase of land, materials, construction, equipment, and services rendered. Operation and management (O&M) costs include estimates of maintenance, and fixed and variable operational costs. The URVs represent what it would cost to produce that water over a specific term. The present value (PV) used in the URV is calculated in US dollars based on costs estimated

Table 1. Assumed efficiencies of evaporation suppression (based on literature), capital, and O&M costs of the selected technologies. Data sources are provided in the text.

Technology solution	Suppression efficiency (%)	Capital costs (USD/ha)	O&M costs (USD/ha per annum)
Monolayer[1]	20	4 464	843
Shade cloth[2]	70	75 157	376
Floating cover hard[3]	80	128 518	75
Floating cover soft[4]	90	112 735	90

[1]Flexible Solutions, 2017, [2]Netpro, 2017, [3]ECS, 2017, [4]SCLI, 2018

at July 2017 values. In this calculation, the term is 20 years. Social discount rates are varied to provide three possible financial scenarios. This study does not go into substantial detail on all of the sources of variation that could contribute to capital and operational and maintenance costs but is more indicative and illustrative of the methods employed. Evaporation rates are varied in three scenarios, using as a median value the evaporation rate calculated over 1 year with the Penman-Monteith method, on the basis that different climatic factors, particularly rainfall, cause annual differences in evaporation (Chapman et al., 2021). Combinations of different evaporation and discount rates provide a sensitivity test of the movement of the URV due to varying inputs to the key variables.

RESULTS

Estimates of evaporative losses at Piketberg

The mean daily Penman-Monteith ET_o, modified for an open water surface, was 4.92 mm/d, which translates to annual use evaporation from open water bodies in the area at 1 796 mm/a (Fig. 2). Daily wind speeds averaged 12.5 km/h during the growing and irrigation season, with daily maximum mean speeds reaching 34.4 km/h and peak gust speeds at 137.6 km/h.

Mean annual Symons pan evaporation observations for Misverstand Weir and Withoogte Purification Works were 1 965 and 1 706 mm/a respectively. Converted to a lake equivalent, these values are 1 631 and 1 416 mm/a, respectively.

The efficiency at which reservoirs can store water influences the economics of evaporation suppression. In this study, the capacity/surface area ratio determines the efficiency of the reservoir, which will then have an impact on the economics of any evaporation suppression action. The reservoir with the greater capacity-to-surface area ratio (Avontuur) at 6% loses less of its annual capacity for evaporation than the Buchu reservoir, which can lose about 26% (Table 2). These values were derived from a simple simulation of reservoir utilisation from full supply capacity (FSC) at the end of the rainy season to 30% at the end of the irrigation season. The simulation used the inverse of a constant similarity of the capacity/surface area ratio to scale evaporative losses from each dam's declining water surface area as water levels fell.

URV values

Table 3 presents the results of the calculation of the URVs for the different suppression technologies, using different evaporation scenarios and different discount rates. Three evaporation scenarios are presented, which are close to the range of inter-annual variation of evaporation in that region, informed by the Penman-Monteith calculation and the inter-annual variation in

Table 2. Reservoir storage efficiency in terms of capacity that can be potentially lost to evaporation

Dam	Capacity/surface area ratio @ FSC (m^3/m^2)	% Annual capacity lost
Avontuur	16.25	6%
Buchu	4.03	26%

Table 3. A unit reference value (URV) comparison of the cost efficiencies of different evaporation suppression technologies; URV units at 2017 currency values (USD/m³)

Evaporation scenario	Discount rate	Monolayer (USD/m³)	Shade cloth (USD/m³)	Floating hard cover (USD/m³)	Floating soft cover (USD/m³)
Low: 1 600 mm/a	6%	0.05	0.59	1.62	1.89
	7%	0.05	0.63	1.74	1.99
	8%	0.06	0.66	1.86	2.17
Medium: 1 800 mm/a	6%	0.04	0.52	1.43	1.68
	7%	0.05	0.56	1.54	1.76
	8%	0.05	0.59	1.65	1.93
High: 2 000 mm/a	6%	0.04	0.47	1.29	1.51
	7%	0.04	0.50	1.39	1.59
	8%	0.05	0.53	1.49	1.74

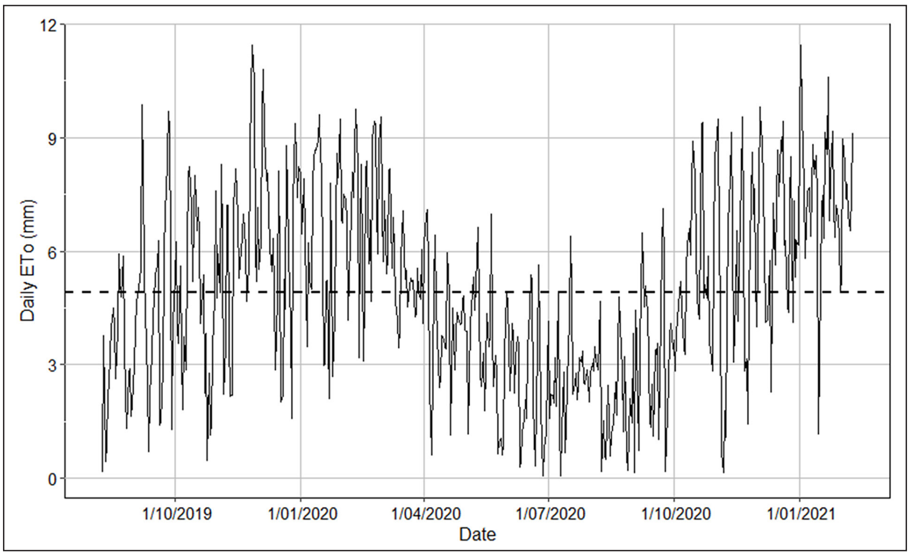

Figure 2. Daily Penman-Monteith ET_o estimates using Eagle's Pride met station (August 2019–February 2021) and modified for an open water reference surface. The daily mean is indicated by a dashed line.

Symons pan data in the district, but with longer time-series than the data presented in Fig. 2.

The URVs presented here are minimum values. Each suppression technology is expected to be utilised in circumstances with a constant water surface and is not approved in reservoir areas that may dry out when water levels fall. This not only has the potential to damage the infrastructure, but also implies capital and operational costs in that area while having little influence on evaporation. This reduces the denominator value in the URV equation described above, or effectively increases the URV.

DISCUSSION

The URVs given in Table 3 shows a substantial range of values. In the following order of increasing values, the URVs of monolayer films, shade cloth, floating hard and soft covers, lie on an ascending cost curve. The monolayer application URV is an order of magnitude lower than any of the others and is the most competitive, price-wise, of all options. Its low capital, operating, and maintenance costs are responsible for the lower URV in comparison to the other methods. Nevertheless, it suffers the serious drawback of being highly susceptible to wind and naturally has low efficiency. Given that daily mean wind speeds at the site are 50% higher during the growing season than the specified maximum at which the product is effective (8 km/h), this option is unfeasible.

The shade cloth product has high initial capital costs, and dimension limitations put surface cover at not more than 70% on average for the smaller water bodies and 50–56% for the larger water bodies (Craig et al., 2005). The shade cloth option is not feasible for larger reservoirs by reason that excessive infrastructure is then required.

Counter-intuitively, while a floating soft cover appears conceptually to be an attractive, simple, and low-cost option, it is the most expensive of the water cover options according to current price options and the durability of the product. The floating mat product has relatively high initial capital costs. Degradation through damage by animals, wind and solar weathering results in repeat capital expenditure, required every 8 years in this estimate, for rebuilding the system, and requiring 3 sets of capital expenditures over the term of the calculation. There are concerns regarding oxygen exchange with the water column below, with potential negative impacts on water quality. Free-floating mats are also susceptible to strong winds and this will be especially relevant in the larger reservoirs.

The sensitivity evaluations show how the URVs respond to both evaporation and discount rate changes. In general, as the evaporation rate increases, the URV decreases. As the discount rate increases, the URV also increases. Using 3 evaporation scenarios (1 600, 1 800, and 2 000 mm/a) as benchmarks, and with the discount rate held constant, the URVs decrease by −5 to −7% for each 200 mm/a increase in evaporation (Table 3). The decreasing URV as evaporation increases reflects the impact of the rising efficiencies of suppression on the unit costs of water. This occurs because with increasing evaporation the same capital and O&M expenses deliver a greater yield in terms of suppression volumes. This pattern of value change is consistent across the range of barrier technologies. For the discount rate sensitivity evaluation, in which evaporation is constant and the discount rate varies, the URVs vary from 5–10% for each percentage change in discount rate across the technology options. The URV is also highly responsive to the capital costs of the specific technology employed, as expected.

It is useful to contextualize these URVs by comparing them to the URVs of other sources of water. Examples include the raising of the Clanwilliam Dam and a large-scale groundwater system (Berg, 2008). For the wall raising, the equivalent range of URV values of 0.10 to 0.14 USD/m^3 was computed, inflated to 2017 values from the published Berg (2008) data, and discounted at 6–8%. The URV values for a large-scale groundwater project ranged from 0.11 to 0.22 USD/m^3, which are also much lower than that for the various suppression technologies, with the exception of the monolayers.

A comparison with desalination is offered because there have been calls to develop desalination augmentation options for municipal use in the City of Cape Town, although these have never come to fruition, likely a consequence of the substantially higher unit costs of that water. Blersch and Du Plessis (2017) provide estimates for a desalination plant that produces 150 000 m^3/d or ±54 000 000 m^3/a. The 50th percentile scenario (the median of the stochastic range of costs) has URVs ranging between 0.79 USD/m^3 and 0.90 USD/m^3 (Blersch and Du Plessis, 2017). Desalinated water is at the high end of what is feasible, cost-wise, for urban and industrial use and is generally unusable for agricultural purposes.

A comparison of suppression costs with desalination costs gives good insight into the feasibility of the different options. The monolayer option is the most cost-effective but also unusable in high-wind environments. Shade cloth is broadly more competitive with desalination, but its possible application is limited to smaller water surface areas. We concur with Craig et al. (2006) that barrier technologies are only viable for water storage with small surface areas. Even then, the capital costs of intervention are still at the high end for economic use in the agricultural context. The floating hard and soft covers prove to be the most expensive option of all, two-thirds more expensive than desalination, at a minimum. There are other concerns regarding floating covers, including the negative effects of contaminating the stored water with residues from manufacturing processes and especially by leaching during their deterioration through weathering. Secondly, they have a negative aesthetic impact (Martínez-Espinosa, 2021).

The reservoir storage efficiency also influences the economics of creating additional yield through evaporation suppression. Annual capacities lost through evaporation from the two farm dams (Table 2) are about 6% for the larger and deeper Avontuur Dam and 26% for the smaller Buchu Dam through the annual cycle of drawdowns of the irrigation season. The reservoirs have different basin shapes and therefore different water storage efficiencies, indicated by the capacity/surface area ratio. The various reservoir shapes cause a variation in evaporation losses as a fraction of their capacities. To reduce URVs, evaporation suppression should not be installed on areas of the reservoir that would dry up during the annual drawdown. As a result, the reservoir storage basin's shape limits the ability for establishing evaporation suppression. The economics of evaporation suppression are worse for reservoirs with low storage efficiency.

Given the high levels of evaporation prevalent in the study area, the URVs show that the suppression technologies are not sufficient to bring costs of water saving into line with desalination and are far more expensive than dam wall raising and a large-scale groundwater scheme. Desalination is often mentioned as a supply alternative (although not appropriate for this study area), but compared to conventional options (surface and groundwater) it is the most expensive (Van Niekerk and Du Plessis, 2013). More detailed research and refinement of useful technologies may result in different URV outcomes. This study is therefore not exhaustive, but a broad indicator of the likely outcomes of cost-effectiveness analyses of evaporation suppression.

CONCLUSIONS

Evaporation suppression technologies compared here cannot compete, in terms of the current unit costs of water, with either the raising of the Clanwilliam Dam wall or a large-scale groundwater scheme. Two technologies are shown to be more expensive than desalination, while one compares more equally. We conclude that many barrier technologies for evaporation suppression are not economically feasible at current water supply and technology prices. The high unit costs of the resulting additional yields illustrate the need to carefully evaluate the cost-effectiveness of water management strategies before implementation.

These results also show the importance of considering (i) the efficiency of evaporation suppression by each technology, (ii) the environmental durability of specific suppression technologies against environmental hazards, (iii) the impact of repeat capital expenditures over the financing term, (iv) the effects of high operational costs, and (v) the efficiency of reservoir basin storage. By increasing product durability to environmental hazards and by decreasing capital and operational and maintenance costs, the various water surface cover options could offer opportunities for reducing the unit costs of suppression to more reasonable cost ranges. Final values should aim to be cheaper than desalination, which currently may be considered as the upper limit of economic feasibility for alternative supplies of water. The need for periodic capital replacement is one of the biggest cost drivers of these evaporation suppression technologies and the reason why initially cheaper options may prove more expensive when considered over a longer term.

Limitations to this work include the likelihood of errors in the cost estimates. We have not explored a larger range of possible prices and it is possible that suppliers could offer products at lower prices than those given here, or of different durability, potentially with longer capital replacement periods. Nevertheless, the broad conclusions of this analysis likely remain robust. We also conclude that the URV provides a useful way of analysing the cost-effectiveness of different options for reducing water losses.

AUTHOR CONTRIBUTIONS

RA Chapman conceptualised the theoretical approach to the study, undertook the economic calculations, and wrote significant parts of the paper. J de Waal developed the evaporation evaluation approach, undertook relevant calculations, and wrote significant parts of the paper. D Svendsen developed the project data for the farm dams on Piketberg Mountain. All authors commented on previous versions of the manuscript and approved the final manuscript.

FUNDING

The authors declare that no funds, grants, or other support were received for the preparation and submitting of this manuscript.

COMPETING INTERESTS

The authors declare they have no financial or non-financial interests that are directly or indirectly related to this work submitted for publication.

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