ABSTRACT

Evaporation can be a source of water loss from artificial reservoirs used in agriculture. Current methods of covering artificial reservoirs are too costly to use by poor, small-scale farmers. This paper presents a method for using waste PET bottles to reduce the evaporative losses from open tanks. This water-conservation method was tested using eight evaporation pans with daily water-level measurements to record evaporation rate. Four pans were used as controls, two were covered with empty waste PET bottles, and two were covered with bottles partially filled with soil. The experiment showed an average reduction in evaporation by 40% with the PET bottle treatment, with a 90% confidence of reducing evaporation by at least 18%. The addition of soil did not affect the degree of evaporation reduction. Given the local economics of the region surrounding Pune, India, it was found that this intervention can save water at a cost of 0.09 USD/m$^3$.

BACKGROUND AND INTRODUCTION

Agriculture is the main source of water use, representing 70% of global water consumption. In 2013, 25% of the world’s irrigated agricultural systems were withdrawing water faster than the regional replenishment rate (Rengel 2013). This challenge of sustainably managing water is acutely noticed in developing countries. In 2010, India consumed 761 x 10$^9$ m$^3$ of water. 90% of that water was used in agriculture (FAO 2011).

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Evaporation accounts for a little over 2% (16.95 x 10^9 m^3/year in 2011) of India’s effective water consumption (Frenken 2011). This paper proposes the use of waste PET bottles as floating covers to reduce water-scarcity as a less expensive and potentially scalable solution to reduce evaporation from man-made irrigation storage systems by approximately 40%.

Discussions with farmers near Pabal, India identified concerns about the rate of water evaporation from their water retaining ponds, often referred to as ‘irrigation tanks’ in India. They noted that solutions to this problem already exist. Suspended and floating covers have been used to reduce evaporation in industrial applications and with large reservoirs (Yao 2010) These existing solutions cost between 8 and 30 USD/m^2 of reservoir and are too expensive. In addition to being too costly, suspended and floating covers are either unable to handle high-winds or unable to capture rain. This paper proposes and tests a method for using PET bottles as floating covers. These bottles are less expensive than existing evaporation reduction methods. In preliminary tests, it was found that these bottle rotate, exposing water film to air and increasing evaporation. To address this challenge, and to prevent the bottle from being blown away in stronger winds, a small amount of soil was added to each bottle in half of the treatments. Subsequently, it was discovered that square bottles (with rounded corners) naturally resist rotation and may not need to be filled with soil. In either case, bottles blown by the wind pile up on one side of a pond and fall back in to a low energy state. When rain falls on the floating mass of bottles, it merely passes between them.

There are popular concerns about chemicals leaching from PET bottles into water when exposed to sunlight and heat. However, surveys of the literature on chemical leaching has shown that the leaching of dangerous chemicals into irrigation ponds is well below the dangerous limits (Gorbaty 2013).

**MATERIALS AND METHODS**

The experiment consisted of daily measurements taken from 8 evaporation pans, which can be seen in Figure 1, from March 5th to May 24th 2014. This time-window was chosen
because it is the hottest and driest in Maharashtra. Of those 8 pans, 4 were uncovered
controls, 2 were covered with empty PET bottles, and the last 2 were covered with 500 ml
PET bottles containing 10 g of soil. Each pan was made from a rolled piece of metal, welded
into a 400 mm tall, 1.5 meter diameter cylinder and lined with white tarpaulin. Those pans
were filled with approximately 270 mm of water and refilled when empty. A wire mesh was
placed over the evaporation pans to prevent the bottles from blowing away in high wind,
and to prevent animals drinking from the pans. The Vigyan Ashram, based near the village
of Pabal, outside of Pune, conducted the experiment by recording the depth of the water in
each pan every day at 5:00 pm IST. Depth measurements were taken with a ruler mounted
to a stand, for stiffness and repeatability, which was placed in the pan for each measurement.

Variations in the weather would not induce error in the mean-shift because the analysis
is based on the difference in evaporation rates between the control and treatments. Measure-
ment errors were symmetric about the true average evaporation rate because the evaporation
rate is calculated from daily measurements of the water height. The remaining sources of
error could be caused by albedo, surface area, or leakage. Using the same tarpaulin in each
pond ensures that their albedo is similar. The difference in pond surface area caused by
construction is small compared to the effect of PET bottle coverage. Leakage is the only
major source of error that is unaccounted for in the experimental design, which can be found
if the average water level drop increases suddenly. This could be improved in the future by
periodically and randomly changing which pond has which treatment.

Due to the non-normality of the data, which can be seen in Table 1 and Figure 3, the
Bootstrap method with 10^6 resamples was used to evaluate the confidence intervals on the
results (Efron 1979).

RESULTS

The cumulative evaporation rate can be seen in Figure 2. Two of the four control pans
(C1 and C2) have unmeasured evaporation rates between day 46 and day 52 because they
became empty and not refilled. Two other control pans (C3, and C4) were re-filled on day
39, resulting in another unmeasured day. To maintain the parallelism of the results, those days were excluded from the evaporation analysis.

The data has low skewness, because evaporation rates are calculated from a running water-level, making the measurement error symmetric.

The evaporation rate data has high kurtosis. This quality is expected because of the outlying evaporation rates caused by measurement error. These measurement errors are identified by examining the net evaporation rate, and are likely the cause of the long tails. This high kurtosis brings the normality of the data into question, requiring a Bootstrap resampling to test confidence intervals. This kurtosis can be reduced in the future by using a more consistent measurement method such as a sight glass.

One of the empty-bottle treatments began to leak after being refilled on day 51. Those results were left from the final hypothesis testing. However, the data from the first 51 days were used to show that the addition of dirt does not reduce the effectiveness of the solution.

The ANOVA-multicompare in Figure 4, performed in MATLAB, from the pre-leak data showed that there is an insignificant difference between the two treatments, and a significant difference (p = 0.1) between the bottle treatments and the control.

The collected data has a mean-shift from 6.0 mm/day with the control to 3.8 mm/day with the sand-bottle treatment. This is a 2.2 mm/day reduction in evaporation, amounting to a 37% mean shift ($\%_{\text{reduced}} = \frac{\Delta x}{x_{\text{control}}}$). It was found, within a 90% confidence interval, that the average evaporation rate can be reduced by at least 1.1 mm/day (18%). The histogram of the resampling that was used can be seen in Figure 5. The control evaporation rate of 6.0 mm/day closely matches the data presented by the Indian government (Sinha 2006), so the analysis in this paper will be based on the Indian government’s data for yearly evaporation rates in Pabal: 2250 mm/year. It is assumed that the fractional reduction in evaporation remains constant.

**ANALYSIS**

The value of this evaporation reduction method is dependent on the economics of PET
waste and the price or value of water. This section considers the costs and benefits associated
with using waste PET bottles as floating covers by examining the price of irrigation water
and the price of PET bottles. In this paper, the value of the intervention is calculated as
the difference between the cost of water saved, and the cost of covering a pond with PET
bottles.

**Price of Water**

There are many ways to determine the value of water (market price, cost of production,
social value). The most simple metric is the price paid for irrigation water by farmers. This
metric does not capture the value of water in water strained regions, where increased water
could improve or save the yield of a crop, but it does provide a baseline.

There is a large variability in the pricing of water schemes (Cornish 2004; Saleth 1997).
The cost of pumped groundwater is used as the benchmark for the price of water. A farmer
in Pabal, Maharashtra who consumes 100 m$^3$ of water per day on average consumes approx-
imately 300 USD/year in electricity. A pump capable of providing that amount of water
would likely cost about 150 USD and needs to be replaced every 4 years on average. This
farmer would consume about 10,000 m$^3$ of water over the course of 100 days of irrigation each
year. Not accounting for the cost of digging a well, the estimated cost of pumped irrigation
water in Pabal which will be used in this paper is 0.035 USD/m$^3$ of water. This value is
reasonable because it is close to 0.032 USD/kWh; the energy cost of lifting 1 m$^3$ an average
of 30m with a 20% efficient pump and an electricity cost of 0.08 USD/kWh. It should be
noted that other farmers in the region receive subsidized irrigation and only pay 1/10$^{th}$ the
electricity rate that this farmer does.

Other regions in Maharasthra, Aurangabad in this case, have reported groundwater ir-
rigation costs as great as 0.50 USD/m$^3$(Foster 2008). Furthermore, irrigation wells run dry
for many farmers in Pabal after April. Some farmers overcome this challenge by importing
water from nearby reservoirs to irrigate high-value crops such as mango-trees. The cost of
importing water via truck for one farmer was 11.60 USD for one 10 m$^3$ tank truck, and sets
the upper bound for acceptable water costs.

**Price of PET Bottles**

The net value of using PET bottles for irrigation needs to include the value of those PET bottles, either as the opportunity cost or the price to purchase. This determines the cost-benefit of using these bottles for evaporation reduction.

The price of recycled PET bottles in India has been reported to vary from 0.03 USD/kg to 0.02 USD/bottle (Dasgupta 2008). It was found that wholesalers in Pune typically purchase PET scrap for between 0.50 and 0.67 USD/kg (Gorbaty 2013). The value 0.58 USD/kg will be used in this calculation. The PET bottle used in this calculation weighs 20 g. The common PET bottle, seen in Figure 6, has a height of 267 mm and a width of 76 mm. This gives a cross-section of approximately 0.02 m². Under these assumptions, the cost of covering an irrigation tank is approximately 0.82 USD/m².

The recorded mean-reduction in evaporation demonstrated in this paper is approximately 40 %. The average annual evaporation rate presented above comes from a report published by the Government of India’s Central Water Commission (Sinha 2006).

If it takes 1 minute to add soil to a bottle, and a typical unskilled laborer is paid 0.30 USD/hour, it will cost an additional 0.005 USD/bottle. The cost of transporting bottles can vary significantly, and is left out of this calculation. Note that many regions that use water tanks as storage will be in places with low population density and low income. This fact will require that the bottles be shipped in. The regional cost of transporting whole PET bottles will need to be considered. One estimate of shipping costs is provided below.

A summary of the analysis presented in this paper, with additional upper and lower bounds for estimations, is in Table 2. The estimated cost to conserve water with PET bottle floating covers, assuming that the bottles will last for five years, is 0.09 USD/m³ of water. This is greater than the estimated cost of pumping water in Pabal; slightly less than the cost of pumping water in Aurangabad; and less than cost of importing water. There are many places in India where water cannot be found in ground-wells during the summer season. In
those places the PET bottles could enable increased yield in addition to reduced costs. Pabal is one of those locations.

**PET bottle availability**

The availability of PET bottles affects how broad of an impact that this innovation could have. It is estimated that Pune produces about 1,168 tons of PET bottles/year (Gorbaty 2013). The most common irrigation tank size in Maharashtra is 30 m wide by 30 m long, and 3 meters deep. With a surface area of 900 m$^2$, it would take approximately 45,000 1L bottles, or 900 kg, to cover one typical tank. If all PET bottle waste produced by Pune were used as floating covers, they could cover approximately 1,300 tanks each year. There are a total of 208,000 irrigation tanks in India (Vaidyanathan 2001). If the bottles last 10 years, 16 cities of equivalent size to Pune would be required to cover all of the irrigation tanks in India.

Shipping the bottles have been estimated to cost 0.66 USD to ship 2000 bottles 1 km (Gorbaty 2013). At 0.00033 USD/bottle/km, the transportation costs for bottles with 0.02 m$^2$ cross-sectional area are 0.0165 USD/m$^2$/km. At this rate, shipping the bottles 50 km to an irrigation tank doubles the cost of the intervention, putting it at 0.18 USD/m$^3$. Adapting the solution to keep the bottle sources as local as possible will be important to preserving the economic value of this intervention.

**CONCLUSION AND FUTURE WORK**

This paper identifies a method for putting a common waste to use for reducing water evaporation by at least 18% ($p = 0.1$) with a mean reduction of 40%. The effect of using PET bottles as floating covers has been demonstrated in the village of Pabal, India, near Pune. It has been shown that the cost of this intervention can be greater or less than the value of the saved water depending on the context. Compared to other interventions, this can save water at 1/3rd the cost or less (Sinha 2006).

Due to the cost of PET bottles, this solution will be effective in regions where water is scarce and waste PET bottles are available. In poor areas with low-population density, the
bottles will need to be shipped to the irrigation tanks, adding a cost to the solution that will need to be taken into account.

This paper also discusses the nature of data collected remotely with high measurement induced kurtosis. The measurement method described above produces statistically useful data with a simple, and low-cost setup when combined with a bootstrap analysis. This setup can be scaled to engage farmers in different regions of India to test and compare this and other evaporation reduction methods.

While this paper focuses on the use of waste PET bottles as floating covers in India, this solution will have even more value in parts of the world where water is more expensive and evaporation rates are very high. The yearly evaporation estimate in Pune is 2250 mm/year. In places like Australia, which also use open water storage tanks, annual evaporation can be as great as 3,000 mm/year (Craig 2005), further increasing the value of this intervention. The application of this solution to other water scarce regions in the world should be investigated further.

Filling the bottles with soil accounts for $\frac{1}{3}$ of the cost of the bottles. In some regions, the soil filling may be unnecessary if the winds are not strong enough to blow the bottles away. Square bottles (which have more resistance to rotation) could be used without soil if the dynamics of bottle rotation, which can bring a film of water to the surface which then evaporates, are better understood. A further benefit of reducing evaporation is that many farmers currently do not use the last bit of water in their pond because evaporation has caused such a dramatic increase in salt or other chemicals. Additional future work will include studying the effects of reducing the concentration of these undesired chemicals in the water by reducing evaporation.

ACKNOWLEDGEMENTS

We would like to thank Vishal Jagtap, Dr. Yogesh Kulkarny, and the rest of the Energy & Environment section of the Vigyan Ashram for conducting the evaporation pan experiment, evaluating water quality, helping our understanding of small scale farming around Pune, and
their excellent hospitality.
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TABLE 1: The skew and kurtosis of the datasets. The very high kurtosis indicates that the data is not normal. Thus the Bootstrap method is used to find confidence intervals.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Skew</th>
<th>Kurtosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0.59</td>
<td>11.57</td>
</tr>
<tr>
<td>Empty Bottles</td>
<td>3.63</td>
<td>31.76</td>
</tr>
<tr>
<td>Sand-filled Bottles</td>
<td>0.64</td>
<td>12.40</td>
</tr>
</tbody>
</table>
TABLE 2: A summary of the estimated price of water conserved by using PET bottles as floating covers.

<table>
<thead>
<tr>
<th>Value</th>
<th>Optimistic</th>
<th>Estimate</th>
<th>Pessimistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price of Water [USD/m³]</td>
<td>1.16</td>
<td>0.50</td>
<td>0.035</td>
</tr>
<tr>
<td>Price of PET Waste [USD/kg]</td>
<td>0.03</td>
<td>0.58</td>
<td>0.75</td>
</tr>
<tr>
<td>Bottle Weight [g]</td>
<td>20</td>
<td>20</td>
<td>28</td>
</tr>
<tr>
<td>Cross-section [m²]</td>
<td>0.028</td>
<td>0.02</td>
<td>0.012</td>
</tr>
<tr>
<td>Avg. Yearly Evaporation [mm/year]</td>
<td>2250</td>
<td>2250</td>
<td>2250</td>
</tr>
<tr>
<td>Evaporation Reduction [%]</td>
<td>58</td>
<td>40</td>
<td>18</td>
</tr>
<tr>
<td>Bottle lifetime [years]</td>
<td>20</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>Bottle Price [USD]</td>
<td>0.001</td>
<td>0.012</td>
<td>0.015</td>
</tr>
<tr>
<td>Filled Bottle Price [USD]</td>
<td>0.006</td>
<td>0.017</td>
<td>0.020</td>
</tr>
<tr>
<td>Filled Coverage Price [USD/m²]</td>
<td>0.28</td>
<td>0.82</td>
<td>0.98</td>
</tr>
<tr>
<td>Cost of Saved Water [USD/m³]</td>
<td>0.01</td>
<td>0.09</td>
<td>2.42</td>
</tr>
</tbody>
</table>
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5. A histogram of resampled with replacement. It shows that 90% of resampled days reduce evaporation by at least 1.1 mm/day.

6. An evaporation pond from the experiment with the empty bottle treatment.

Simon, May. 20, 2014
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