

EVAPORATION SUPPRESSION RESEARCH AND APPLICATIONS FOR WATER MANAGEMENT

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INTRODUCTION

Evaporation of water from reservoirs, rivers, and agricultural fields results in major losses of critical water resources, especially in arid regions of the world. In arid regions, evaporation can account for as much as 25 to 30% of the total consumptive use of surface water. Because evaporation is such a large part of the water budget in arid regions, evaporation suppression has been studied for decades. Research has shown that surfactants, which modify the surface tension of the water surface, are very effective in the laboratory in suppressing evaporation. Recent research has shown that environmentally innocuous surfactant monolayers covering water surfaces can reduce the rate of evaporation by as much as 40 to 70%, resulting in substantial water resource savings. However, there are technical challenges that have limited the deployment of surfactants and surfactant films on lakes and reservoirs. Wave action created by winds across large open-water surfaces tends to break up the monolayer film, necessitating the need for surfactant reapplication to repair or replace the film. The cost of frequent reapplication of synthetically produced surfactants can quickly overcome the benefits of reduced water loss. An inexpensive surfactant capable of reducing evaporative loss and demonstrating long-term effectiveness is needed to improve the cost effectiveness and efficiency of surfactant based evaporation suppression.

Researchers at Sandia have been investigating the possible use of microbiologically produced surfactants with characteristics similar to proven synthetically produced surfactants to meet this challenge. In recent years, biosurfactant applications in crude oil recovery, health care, and food processing have been extensively investigated. As biosurfactant technology improves, microbiologically produced surfactants could become competitive with synthetic surfactants in functionality and efficiency, but with significantly reduced production and deployment costs. Recent research into evaporation suppression has identified and assessed effective synthetic surfactants, analogous biosurfactants that can be produced from known heavy surfactant producing microorganisms, ecological issues, and commercial applicability. Additional research will be needed to address overall monolayer functionality and full-scale evaporation suppression efficiency, long-term ecological impact, scale-up potential, and overall cost-effectiveness.

DISCUSSION AND OVERVIEW

Evaporation of freshwater from reservoirs, rivers, and agricultural fields results in major losses of critical fresh water resources, especially in arid regions of the world. In the Rio Grande Basin, e.g., evaporation from the mid-sized reservoir, Elephant Butte, accounts for 15 to 25% of the NM Rio Grande surface water consumptive use allotment each year or 100,000 to as much as 200,000 acre-feet of water each year (Gupta et al. 2002). This is enough water to support the water needs of a city the size of Albuquerque for 2 to 4 years.

The evaporation rate from a water surface is a function of the energy balance equation shown below:

$$E = \Delta H / \rho [1 + K_1 \lambda \rho (\Delta T / \Delta e)]$$

Where: E = evaporation rate

ΔH = change in available heat

ρ = density of evaporated water

λ = heat of vaporization

ΔT = difference between surface and air temperature

Δe = difference between surface and air vapor pressure

Based on this equation, evaporative losses from reservoirs can be reduced several ways including; siting reservoirs in areas with lower temperatures, designing of reservoirs to reduce surface area, or changing the surface pressure. Surfactant films covering water surfaces are known to reduce evaporative loss by changing surface tension (Mansfield 1953; Timblin et al. 1957; Foulds and Dressler 1968; Dressler and Guinat 1973; Moore and Reed 1976; Tang et al. 1993). Recent work at Sandia (Gupta 2002) developed experimental laboratory and field data on evaporation suppression using combinations of emerging molecular monolayer surfactants.

These surfactants are very effective in spreading out and creating thin films approximately one molecule thick. This could allow for very effective surfactant utilization and spreading on large reservoir surfaces. The results are presented in Figure 1. The field tests were conducted in 8-foot diameter pools in Albuquerque as shown in Figure 2.

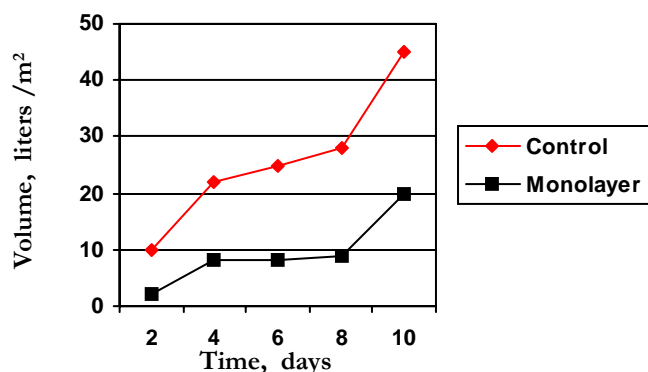


Figure 1. Evaporation Suppression Field Test Results.



Figure 2. Evaporation Suppression Field Tests.

These surfactants are alcohol-functionalized straight chain hydrocarbons, as illustrated by the structure of the twelve-carbon dodecanol (Figure 3a). These surfactants are all food-grade surfactants that are safe and easily available. In general the results show a 60-70% reduction in evaporation over a one-week period. As time increases, the molecular monolayer effectiveness begins to decrease. In evaluation of total dissolved oxygen in the tests, no differences were found between the control and monolayer pools. Earlier studies of the ecological effects of hexadecanol used for evaporation suppression on large ponds indicate a minimal effect on ecological activity primarily limited to suppression of larval mosquito populations and a slight rise in surface temperature (Hayes 1959). The monolayer film usefulness as an evaporative barrier over large water surfaces is reduced over time by susceptibility to environmental insults such as wind and wave action. Wind and wave action across water surfaces tends to break up the monolayer, necessitating the need for reapplication of surfactant to replace or repair the surfactant monolayer film. Depending on the overall effectiveness and cost of the surfactant, reapplications can make this approach to water conservation cost prohibitive relative to the benefit of reduced water loss.

A more effective and less costly surfactant is needed to help realize the potential benefits of evaporation suppression. A simple, inexpensive, on-site surfactant manufacturing and application process is needed to reduce production, transportation, application, and operation costs. One production method that has been suggested is the culturing of surfactant producing microorganisms. Many species of microorganisms are known to produce alcohol- or peptide-functionalized straight chain hydrocarbon surfactants, many with similarity to effective synthetic surfactants. These include (1) sophorolipids produced by the yeast *Candida bombicola*, (2) rhamnolipids produced by the bacterium *Pseudomonas aeruginosa*, and (3) lipopeptides produced by the bacterium *Bacillus subtilis* (Lang 2002). The chemical structures of these surfactants are presented in Figures 3b, 3c, and 3d, respectively.

To meet the necessary requirements, microorganisms capable of large volume low-cost biological surfactant production must be selected. Additionally, the biosurfactants will be required to demonstrate long-term effectiveness under adverse environmental conditions, ecological sensitivity, and compatibility with synthetically produced surfactants. The surfactant yield for any given organism is dependent on the primary carbon source. A sophorolipid yield by *C. bombicola* of 25 to >300 g/l has been reported using glucose and rapeseed oil as primary carbon substrates (Rau et al. 2001). Reported yields of rhamnolipid by *P. aeruginosa* using corn, sunflower, or olive oils as primary carbon sources ranged from 3 to 100 g/l (Haba et al. 2000; Mata-Sandoval et al. 2001; Lang 2002). Glucose and iron or manganese supplements have produced yields of lipopeptide from *B. subtilis* ranging from 2.6 to 3.5 g/l (Sen 1996; Kim et al. 1997; Wei and Chu 1998; Wei and Chu 2002). Biosurfactants can also be combined with varying amounts of synthetic surfactants to improve functionality.

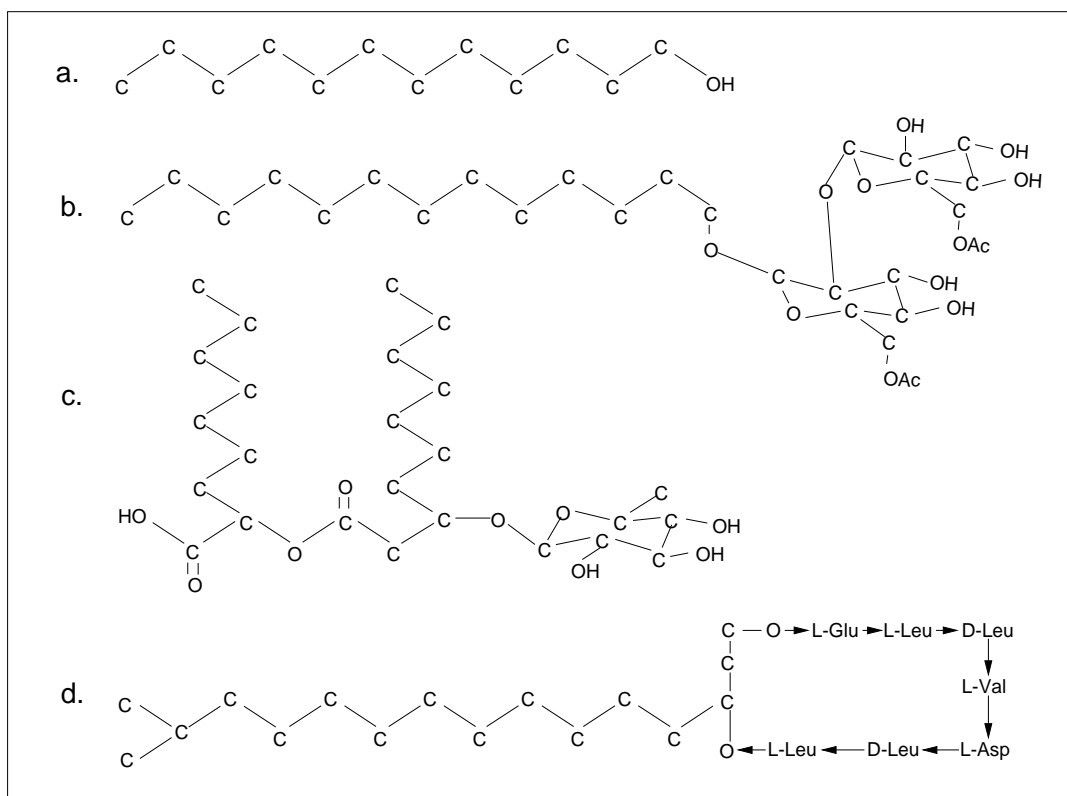


Figure 3. Chemical structures of (a) dodecanol, (b) sophorolipid, (c) rhamnolipid, and (d) lipopeptide.

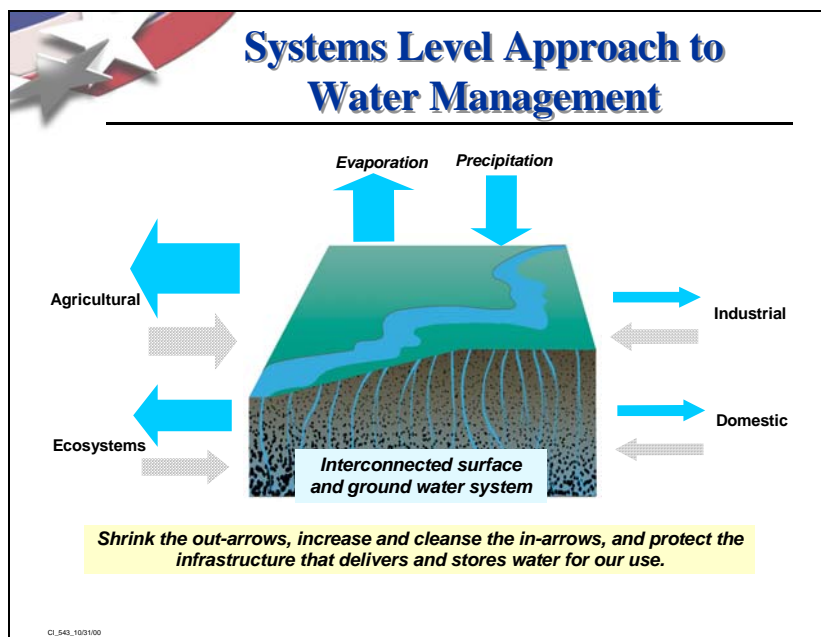
Initial results from laboratory testing of a limited selection of biological surfactants for evaporation suppression showed a performance of 50% less than that of synthetic surfactants. Therefore, additional research will be needed to optimize biosurfactant performance, food source, and yield required for cost effective implementation of this type of approach. Microbiological growth studies using the biosurfactants as the sole carbon and electron donor source, and common soil microorganisms need to be conducted to assess biodegradation potential and biomass production. The ideal biosurfactant would possess complete mineralization qualities and minimal biomass production.

Initial estimates for surfactant evaporation suppression, based on existing biosurfactant yields and estimated suppression performance, and initial estimates of manufacturing and operational costs for large reservoir applications, vary from \$30-\$200/acre foot of water saved. The scale-up and commercial viability aspects of biosurfactant evaporation suppression in terms of functionality, effective life-time, bioreactor design, surfactant production rates, large-scale application, and capital and operational costs must be further evaluated to better refine these estimates. While the costs are preliminary, the estimates though do suggest that evaporation suppression costs are in the ballpark of what water costs may be in the future. Therefore, evaporation suppression, especially with environmentally benign biological surfactants, may have promise to improve water management of large reservoirs in arid regions in the future.

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This picture denotes primary sources and sinks for water on a global scale. Colors denote the quality of water: blue is high-quality water and gray denotes low quality. The thickness of the arrows denotes relative quantities. The central image represents (sometimes interconnected) surface and groundwater reserves.

Agriculture accounts for 75 - 90% of water use worldwide. Some agricultural water is returned to the system through surface runoff and percolation. Poor land management, over use of pesticides and fertilizers, and poor irrigation practices markedly reduce the quality of the water that is returned to the ecosystem.


Domestic water use dominates in the Middle Rio Grande and is growing worldwide. This water can return to the system through surface runoff, or through public infrastructure, e.g., as sewage treatment plants. If not treated appropriately, such contaminated water can further contaminate surface and ground water. It is also a primary cause of death in many countries.

Industrial water use accounts for 5 - 10% of water use worldwide. While this percentage is relatively small, the water returned to the system through surface runoff, water treatment plants, or direct injection into lakes and rivers accounts for a significant portion of water pollution worldwide.

Evaporation of water from reservoirs, irrigation systems, and lakes represents a major water loss in some arid regions. For example, daily evaporation from Elephant Butte Reservoir is higher than the daily domestic water use in Albuquerque.


Precipitation, the source of all renewable water for the ecosystem, contributes to surface water and groundwater (through percolation). Land degradation has a major impact on the quality of water we obtain through precipitation, by interfering with percolation processes and by reducing the quality of surface water through erosion and pollution. Much precipitation also returns to the system as saline water through the oceans.

Ground water reserves have been a major source of water in the last century. However, withdrawal rates far exceed replenishment rates, which will result in severe and irreversible water shortages in the future. In addition, in many cases groundwater is brackish and saline -- rendering it useless for many applications.



Water Use on the Upper Rio Grande


- **Agricultural Consumption ~35%**
- **Riparian Habitat Consumption ~35%**
- **Reservoir Evaporation ~25%**
- **Domestic and Industrial Consumption ~5%**



Evaporation Problem

Water evaporation from reservoirs results in major losses of critical water resources


- **Evaporative losses represent 25% to 30% of the total consumptive use of surface water in arid regions**
- **Reservoir and lake evaporation typically 50 to 80 inches per year in arid regions**
- **Elephant Butte Reservoir evaporation losses range from 50,000 to 250,000 acre feet per year**
- **Evaporation varies by season, 40% of total in summer, 25% in spring, 25% in fall, and 10% in winter**
- **Economic studies suggest water values of \$200 to \$600 per acre foot**



Controlling Evaporative Losses

- **Energy-balance evaporation equation:**


$$E = \Delta H / \rho [\lambda + K_1 \lambda \rho (\Delta T / \Delta e)]$$
 - E = evaporation rate
 - ΔH = change in available heat
 - ρ = density of evaporated water
 - λ = heat of vaporization
 - ΔT = difference between surface and air temperature
 - Δe = difference between surface and air vapor pressure
- **Evaporation can be reduced by reservoir location, change in design and areal extent, addition of covers or surfactants to change surface pressure, alternative storage concepts, etc.**



Surfactant Application Considerations

Large area surface barrier could help mitigate reservoir and lake evaporative losses but would require :

- **Efficient evaporation suppression**
- **Cost effective**
- **Long-term stability**
- **Large area applicability**
- **Environmentally innocuous**



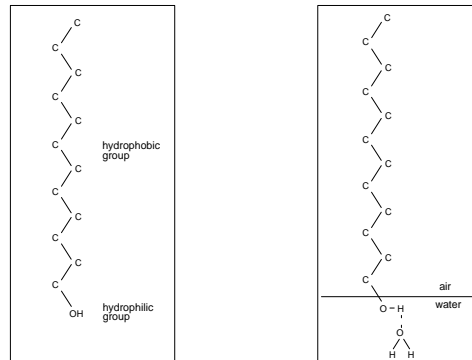
Possible Approach

Fatty Alcohol Surfactant Monolayer Films

- **Advantages**
 - Fatty alcohols readily form monolayer films over water surfaces
 - Numerous studies show fatty alcohol monolayer films reduce evaporative loss (10% to 75%)
 - FDA approved surfactants used commercially for swimming pool evaporation control
- **Issues**
 - Susceptibility to environmental insult (wind) may limit usefulness to smaller areas (sq. miles)
 - Limits on long-term stability (many days)
 - Surfactants may require organic solvents

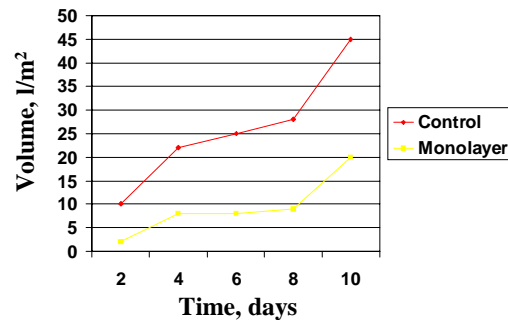
General Technical Approach

Fatty Alcohol Surfactant Monolayer Films



Recent Sandia Test Results on Improved Surfactants

Results from 8 Feet Diameter Pools



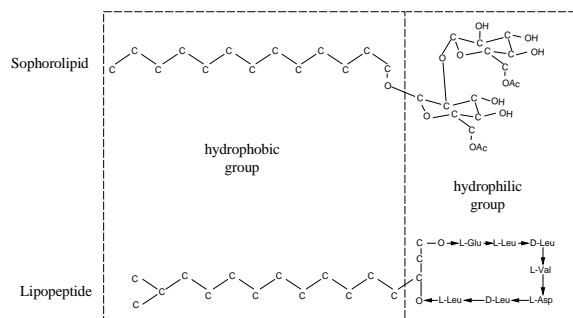
Possible Technical Approach

Biological Surfactant Fatty Alcohol Analogs

- **Advantages**
 - Potentially much more cost effective with on-site production capability
 - Application requires no organic solvents
 - Renewable resource
- **Issues**
 - Non optimized monolayer functionality
 - Current evaporation suppression capability and stability is limited

Technical Approach

Biological Surfactant Fatty Alcohol Analogs



Summary of Current Understanding of Surfactants for Evaporation Suppression

- Long-term pool tests show no difference in dissolved oxygen in monolayer surfactant and control pools.
- Food grade surfactants are easily available
- Biological surfactant appear feasible, but have yet to be efficiently optimized.
- Cost estimates for surfactant evaporation suppression varies from \$30-\$200/acre foot of water saved depending on reapplication rate and time of year.