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ORIGINAL ARTICLE

Evaporation Mitigation Assessment by Self-assembled Nano-thickness Films in Shallow Fresh Water Lake Using Fixed and Semi-Floating Pans

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Abstract

Controlling evaporation plays an essential role in arid and semi-arid water resources systems where it accounts for a considerable amount of reservoirs outflow. In this study, we have evaluated evaporation reduction efficiency of different kinds of self-assembled nano-thickness films. The films consist of six different combinations of stearyl and cetyl alcohols with additives such as jojoba oil, stearic acid, and calcium hydroxide. The study lasted from July to August and utilized two pairs of class A evaporation pans: one pair was semi-floating on Chitgar lake water surface while the other one was located on the shore. The experimental results showed that a monolayer containing 3:1 stearyl to cetyl alcohols with 60% weight of calcium hydroxide had the best performance and could reduce evaporation up to 50% during its three-day lifetime. The study indicated that while the films had no significant side effects on lake water pH, turbidity, and total suspended solids, a slight increase in water surface temperature was observed. It can be concluded that application of such monolayers in areas suffering from high evaporation could be conducive to better water resources management.

Article Highlights

- Self-assembled nano-thickness fatty alcohol films can reduce water evaporation.
- Evaporation was reduced up to 50% by a mixture of St, Ce and $Ca(OH)_2$ on the water surface.
- Using a biodegradable cover is promising for water management of shallow lakes.

Keywords Evaporation mitigation · Self-assembled monolayers · Fatty alcohol · Evaporation pan · Chitgar lake

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1 Introduction

Less than 3% of available water on earth is freshwater (Fitts 2013) and its demand is vastly increasing (Ashoori et al. 2017; Boretti and Rosa 2019; Pouladi et al. 2022), making essential the conservation of existing freshwater resources, especially in dry climate regions like Iran where 90% of its land is arid or semi-arid (Oroud 2015; Hassan and Peirson 2016; Boazar et al. 2019). The average rainfall there is less than one-third of the global average (Madani 2014) and more than half of the country's population is exposed to water scarcity. Two-thirds of the precipitation volumes evaporate before reaching rivers (Frenken 2009) and average water evaporation is more than three times of the global average (Abbaspour et al. 2009). Therefore, evaporation reduction methods could be of great help in preserving water, where evaporation control plays an essential role in water resources management (Yazdanpanah et al. 2013; Sebbar et al. 2019; Elkatoury et al. 2020; Mohammadi et al. 2022).

Physical barriers and chemical films have been frequently recommended in evaporation mitigation studies (Assouline et al. 2011; Hartzell 2016; Aminzadeh et al. 2018). Physical structures such as shading (Alvarez et al. 2006; Gallego-Elvira et al. 2011), and different floating covers like Solar PV (Farrar et al. 2022), Aqua-Cap (Yao et al. 2010), plywood floats (Benzaghta et al. 2013), hollow PET bottles (Simon et al. 2016), modular covers (Hassan et al. 2015), floating plates (Li et al. 2021) and balls (Martínez-Espinosa 2021) have been proposed to be placed on the water body surface to diminish energy and mass exchanges between the water surface and the surrounding air (Shahraeeni et al. 2012; Haghighi et al. 2013). Physical methods are suitable for water reservoirs which are less than 10 ha while chemical covers are recommended as economical techniques for large water bodies (Craig et al. 2007; Haghighi et al. 2018). In the chemical method, a nanometric Self-Assembled Monolayer (SAM) consisting of long-chain self-spread molecules is dispersed on the water surface to form a molecular film at the air-water interface, which prevents the water molecules from evaporating (Mozafari et al. 2019; Mohammadi et al. 2022). Since surfaces and interface molecules have some repelling and attracting interaction at small length scales (Lee 2013), designing multifunctional interfaces on molecular level has gained importance in different scientific fields such as chemistry, physics, biology and nanotechnology (Gooding and Ciampi 2011; Lee 2013). Self-assembly is a natural way to organize molecular structure without any external force. Self-assembled monolayers (SAMs) form on a surface due to a specific functional group that has a strong affinity for a particular surface (Rudra et al. 2017). They have been used in various studies for designing new coatings and packaging (Gooding and Ciampi 2011; Huang et al. 2019; He et al. 2019; Wang et al. 2020; Hostert et al. 2021; Mittal et al. 2021). Biodegradable molecule based SAMs are promising covers for using on water-air interface for reducing evaporation. One of the most common suggested chemical materials for evaporation suppression is fully saturated alkyl chains consisting of more than 12 carbons with a polar group, including long chain fatty alcohols such as stearyl or cetyl alcohols (Mcjannet et al. 2008; Barnes 2008). While one tail of these molecules is hydrophilic that will settle on the water surface, the other tail is hydrophobic which spreads on the air-water interface. Thus, they stand next to each other on the water surface and act as a unique thin film (Pittaway and Ancker 2010; Lombardo et al. 2015). They spontaneously spread on the surface and could decrease evaporation up to 45% in reservoirs and lakes with areas less than 10 km^2 (Mcjannet et al. 2008; Fomina et al. 2014). Also, evaporation reduction of the monolayers has been reported up to 70% in smaller scales and limited conditions such as in class A evaporation pans and lab-scale tests (Gallego-Elvira et al. 2013; Mozafari et al. 2019). Using such layers is more reasonable than physical covers in periods when evaporation is higher and wind flow is not too heavy, as they display better stability at lower wind speeds (Prime et al. 2012; Mozafari et al. 2019). Small amounts of these materials are enough to cover a wide area. For instance, about 20 g of stearyl alcohol is enough to cover a hectare. Although they have a relatively short lifetime and may be degraded by microbial activities (Craig et al. 2005; Pittaway et al. 2015), they are environmentally safe and have less impacts on lake water quality (Mcjannet et al. 2008; Fisk et al. 2009; Mohammadi et al. 2022). Functionality of commonly suggested materials, i.e., stearyl alcohol and cetyl alcohol can be enhanced by using them together or with additives. It is known that, as an additive, calcium hydroxide enhances spreading of layers. In the present paper, we studied other additives which may also be helpful for film functionality, such as stearic acid and jojoba oil.

Evaluating real time evaporation reduction efficiency of different materials has been a challenge. Although different studies have been done on evaporation suppression efficiency of chemical coverages, no standard setup has been introduced to present how much a monolayer will reduce evaporation. Aminzadeh et al. (2018), Yao et al. (2010) and Mcjannet et al. (2008) used energy balance and empirical formula to predict evaporation from open water surface while covered with physical or chemical elements. Such a method cannot completely predict real evaporation since each empirical method and formula has its inherent limitations. For example, energy balance methods do not consider wind speed while mass balance methods ignore energy exchange of the lake (Abtew and Melesse 2013). Using more combination methods are not applicable for every environment because of too many input requirements and field observations (Finch and Hall 2006; Mozafari et al. 2019) used monolayers in laboratory-scale tests (small containers) which is far from real situations of field measurements in lakes. Semi-real studies on two comparative reservoirs (like fixed class A evaporation pans) have been performed on fresh and salty water (Alvarez et al. 2006; Hassan et al. 2015; Hassan and Peirson 2016; Saggaï and Bachi 2018; Mohammadi et al. 2022). They have their own errors as stagnant water inside the fixed pans fails to completely simulate lake conditions. As far as we know, no previous study has used floated pans since their operation and setup is rather difficult. In this study two comparative pairs of fixed and semi-floating pans on Chitgar lake have been used in order to evaluate films efficiency.

Chitgar lake is the largest artificial recreational lake in Iran. The main cause of water level drop in the lake is evaporation; it has been estimated that about 2×10^6 m^3 is evaporated annually (STPCEC 2012). The Kan River is the only water supplier of the lake, which is also directed toward agricultural lands in the south of Tehran and Fashafouyeh plain, and finally, flows into Ali-Khan wetland (Skardi et al. 2020). The plain is in a critical situation of groundwater level (Bagheri et al. 2020), and Ali-Khan wetland has recently been exposed to drought. In other words, Chitgar lake contributes to water reduction in the downstream river (Khorasani et al. 2018). Moreover, the high growth of algae due to eutrophication affects the recreational usage and utilization of the lake (Khorasani et al. 2018), which is another main challenge that the lake is facing since its operation. These two challenges can be solved by reducing evaporation. This is especially becoming more important in summer when most evaporation occurs besides internal feeding from sediments loaded to the lake from the Kan river which causes an increase in phosphorus concentration that leads to algal

Fig. 1 Map of the study area showing the location of Chitgar Lake in Iran's capital, Tehran

bloom (Khorasani et al. 2018; Yan et al. 2019). In this case, reducing evaporation of the lake can help improve the eutrophication problem and save more water under drought conditions and water shortage problems of Tehran as a model for other cities which have encountered water management problems (Madani 2014; Ravanshadnia et al. 2015; Ardalan et al. 2019; Motlaghzadeh et al. 2020).

2 Method and Field Facilities

2.1 Site Description and Field Experiments

Chitgar lake is a large man-made infrastructure located in Iran's capital, as shown in Fig. 1. The water surface area, the reservoir volume, the maximum water depth, and the mean water depth at normal water level are 1.3 km^2, 7×10^6 m^3, 9.5 m and 5.4 m, respectively (STPCEC 2012). The lake has been designed to improve urban development, recreation, green space, and to attract tourists. The bottom of the lake is separated from the bed by geomembrane and is not connected to any groundwater source, so it can be considered as a closed lake. The inflow into the lake comprises seasonal rainfall and Kan River runoff while the main outflow is evaporation. The evaporation rate of the lake has been estimated to be higher than 8 mm/day in August (Behrouzi and Chini 2016). This means that approximately 1×10^6 m^3 of water, equivalent to the water demand of a city with a population of about 100,000 people, evaporates during the summer.

Two pairs of standard class A evaporation pans were used for thin film application evaluation. They can be exposed either above the ground or mounted on floating platforms on the water surface (WMO 2008). The water inside ground pans is stagnant while floating ones face waves and are turbulent, which may better represent lake conditions. Therefore, we used two pairs of pans to study the effect of thin films on the water evaporation in wavy and still water conditions: one pair was placed in land and the other semi-floating one was positioned on the water surface as shown in Fig. 2. In each pair, one pan covered with monolayer was the test pan and the other uncovered one was the control pan. The most appropriate locations for conducting tests were found to be in and around the middle island to meet World Meteorological Organization's standards, i.e., open air and airflow environment, away from any shading. Land pans were mounted on wooden platform (Allen et al. 1998; WMO 2008). Wire nettings were mounted on all pans to prevent birds from using

Fig. 2 Two pairs of class A evaporation pans at Chitgar Lake, One pair on the ground and another one semi-floating on the water body

pan water. Such a netting reduces evaporation in pan by 10% (Allen et al. 1998) which has the same effect on all pans. At each stage of the experiment, all pans were first filled by the lake water to the depth of 20 cm based on the recommendation of standard usage of class A evaporation pan (Allen et al. 1998). Experiments were conducted during summer of 2019, in July and August. Each experiment continued for 3 days until the films were degraded. After this period, the water level inside the control pans usually drops near the lowest limit of the standard, which causes an error in evaporation rate (Allen et al. 1998). Water inside the pans cannot be replenished because of the monolayers break and drowning due to water infusion. Assuming that the evaporation of the control and test pans are Δh_c and Δh_t, respectively, and R_i is the evaporation reduction percentage of the film *i*, the evaporation reduction percentage of each film can be calculated using Eq. (1):

$$R_i = \frac{\Delta h_c - \Delta h_t}{\Delta h_c} \times 100 \tag{1}$$

The water quality parameters including pH, turbidity and total suspended solids (TSS) of each pan were measured before and after each test by “Hack HQ40D”, “LaMotte 2020 turbidity meter” and “Hack DR2800” probes, respectively, to determine the effect of the film on water parameters that may affect the recreational use of the lake (Keeler et al. 2015; Chang et al. 2020). Also, to investigate the effect of meteorological parameters on the behavior of the monolayers, air temperature and wind velocity were gathered online every three hours by selecting the lake location from “Dark Sky[1]” corporation and the water surface temperature was measured in the field.

2.2 Film Formulation and Application

Different combination of stearyl alcohol (St, $CH_3(CH_2)17OH$), cetyl alcohol (Ce, $CH_3(CH_2)15OH$), stearic acid (Sa, $CH_3(CH_2)16COOH$) and Jojoba oil (JO) materials were used to form a molecular film on water surface. St and Ce were selected based on their recommendation in past studies (Craig et al. 2007; Mcjannet et al. 2008; Prime et al. 2012) and they have a chain length of 18 and 16 carbons, respectively. While Ce has a lower molecular mass than St and disperses more rapidly on the water surface, St provides a more robust film because of the longer carbon chains (Prime et al. 2012). Stearic acid is also a non-toxic fatty

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[1] www.Darksky.net.

Table 1 Number of monolayers (ML) and total required mass for each component of the films (g/m^2)

Film number	Stearyl alcohol (St)	Cetyl alcohol (Ce)	Stearic acid (Sa)	Calcium hydroxide (CH)	Jojoba oil (JO)
Film 1 (F1)	60 ML ($0.12\ g/m^2$)	-	-	-	-
Film 2 (F2)	-	60 ML ($0.1\ g/m^2$)	-	-	-
Film 3 (F3)	30 ML ($0.06\ g/m^2$)	-	-	-	30 ML ($50\ \mu L/m^2$)
Film 4 (F4)	45 ML ($0.1\ g/m^2$)	15 ML ($0.03\ g/m^2$)	-	-	-
Film 5 (F5)	30 ML ($0.06\ g/m^2$)	10 ML ($0.02\ g/m^2$)	20 ML ($0.05\ g/m^2$)	-	-
Film 6 (F6)	45 ML ($0.1\ g/m^2$)	15 ML ($0.03\ g/m^2$)	-	60% weight of total mass ($0.2\ g/m^2$)	-

acid that has the same chain length as stearyl alcohol (Zhen et al. 2015), and can improve the interaction between film molecules and the subfilm water (Brzozowska et al. 2012). Jojoba oil is a natural liquid (Matsumoto et al. 2019) mostly composed of esters with a chain length of 40 and 42 carbons (Sánchez et al. 2015) with high oxidant and temperature stability (Le Dréau et al. 2009; Sánchez et al. 2016), so that they can be used as evaporation mitigation material. Additives like calcium hydroxide (CH) can be used to overcome difficulties of practical films such as loss from water surface and low respreading rate (Barnes 2008; Mozafari et al. 2019). Moreover, as presented in Table 1, small amounts of these materials are enough to cover the water surface, while being available and economical. Each molecule of St, Ce, Sa and JO covers areas of 23 $Å^2$ (Prime et al. 2012), 24 $Å^2$ (Prime et al. 2012), 20 $Å^2$ (Lendrum and McGrath 2009), and 77 $Å^2$ (Caruso et al. 2018) on pure water surface in a monolayer of them, respectively. Considering the surface area and molecular mass, the required amount to form a monolayer (i.e., closely packed molecules) on the water surface can be calculated using Eq. (2):

$$Monolayer\ Mass\ (g) = \frac{Total\ Area\ (cm^2)}{Area\ of\ one\ Molecule\ (\frac{A^2}{molecule}) \times 10^{-16}} \times \frac{Molecular\ weight\ (\frac{g}{mol})}{6.023 \times 10^{23}\ (\frac{molecule}{mol})} \tag{2}$$

For example, 1.91 mg of Ce is required to disperse a layer of Ce on a class A pan with an area of 1.14 m^2. In order to better disperse the monolayers on the water surface, they can be dissolved in a suitable volatile solvent such as ethanol. In this case, the solvent will evaporate in a short time and the thin layer will remain on the surface (Prime et al. 2012). The proper composition and weight of materials for the film to be added to the solvent were found based on our laboratory scale test results on fresh water and field experiments using evaporation pans containing Chitgar lake water. Used materials in each film is equal to sixty times the amount of fatty alcohols and acids required to form one monolayer of them, whose total thickness is about 100 nm. They were prepared with 5 mg/mL concentration in ethanol as solvent and sprayed on each test pan. The calculated number and required mass of the corresponding molecular layers for each film used in this study are shown in Table 1.

3 Results and Discussion

Average evaporation reduction percentages of the film (*R*), which are expressed in Eq. (1), are shown in Fig. 3 for the 1st, 2nd and 3rd day in addition to the Saved Total Water Height caused by the film type (STWH), average air temperature (Tair), and wind speed (w) during the experiment. Film 1 (F1) containing only St presented rather similar evaporation reduction *R* on the land and semi-floating pans for 72 h. During this period, although *R* of land and floating pans are similar, F1 on land pan could save 2 mm of water depth more than on the floating pan, which is due to the higher evaporation in land compared with the pans in contact with lake water. Film 2 (F2) containing only Ce with a shorter chain length and higher dispersion rate indicated lower performance than F1 with an *R* of about 16% on each pan. This film disappeared after the 1st day mainly due to utilization by bacteria (Craig et al. 2005; Barnes 2008). Using longer chain molecules besides some additives like JO increases film efficiency (Prime et al. 2012; Mozafari et al. 2019). JO, as a long chain ester, was mixed with St to make F3 film which could present higher evaporation redundancy in the 1st day, but indicated lower lifetime because of higher wind speed and temperature. Under windy conditions, using a component to fill in films cracks and help respreading becomes important (Mozafari et al. 2019). In order to overcome this problem, St and Ce can be mixed in which the one with shorter chain length (Ce) helps spreading rate and filling in the cracks while the longer one (St) acts more as an evaporation retardant (Prime et al. 2012). F4, consisting of 3:1 St to Ce, showed a higher *R*, more than 50% for the 1st day, indicating a closer molecular packing film and a synergistic effect of St and Ce. Reduced *R* in the 2nd day was probably due to fast degradation of Ce which was seen in the F2 experiment. Based on a previous study on Urmia Salt Lake water evaporation suppression, the Sa was added to the mixture to improve layer performance on the surface (Mohammadi et al. 2022). F5 showed rather good performance on the 1st day but shorter life time compared with the results of Mohammadi et al. (2022). This is because of high salt concentration in Urmia Lake water and lack of microorganisms. In order to improve stability and increase spreading rate of the layer, CH was added to the F4 composition to make F6 sample which resulted in more than 50 and 40% evaporation reduction in the 1st and 2nd day on both land and floating pans, respectively. These values agree with the results of Mozafari et al. (2019) on small containers in laboratory tests. The CH dissolves in water and makes positively charged calcium ions that raise spreading rate due to the positive repel force. It enhances stability of the monolayer as we observed in the presence of wind velocity of 5 m/s (Fig. 3). High wind speed affects functionality and life time of monolayers, which may collapse and dump them in water (Mcjannet et al. 2008; Mozafari et al. 2019). It also brings monolayers to the reservoir edge and makes parts of the water surface uncovered. F6, as the most effective film, could save more than 12.5 mm of water during three days. By using this film on lake water, it is anticipated to reduce evaporation from more than 8 mm/day in summer to 4 mm/day (Behrouzi and Chini 2016), therefore saving about 5000 m^3/day of water for Ali-Khan wetland, Fashafouyeh plain and agricultural demand in downstream. Moreover, reducing evaporation will diminish the concentration growth of the phosphorus materials, and hence, it could help suppress eutrophication of the lake.

The lake water quality parameters, including pH, turbidity, and TSS before each test were measured; their average values were 8.4, 4.5 (NTU) and 6.5 (mg/l), respectively. Their average values after each test compared to the beginning showed that the films had no significant

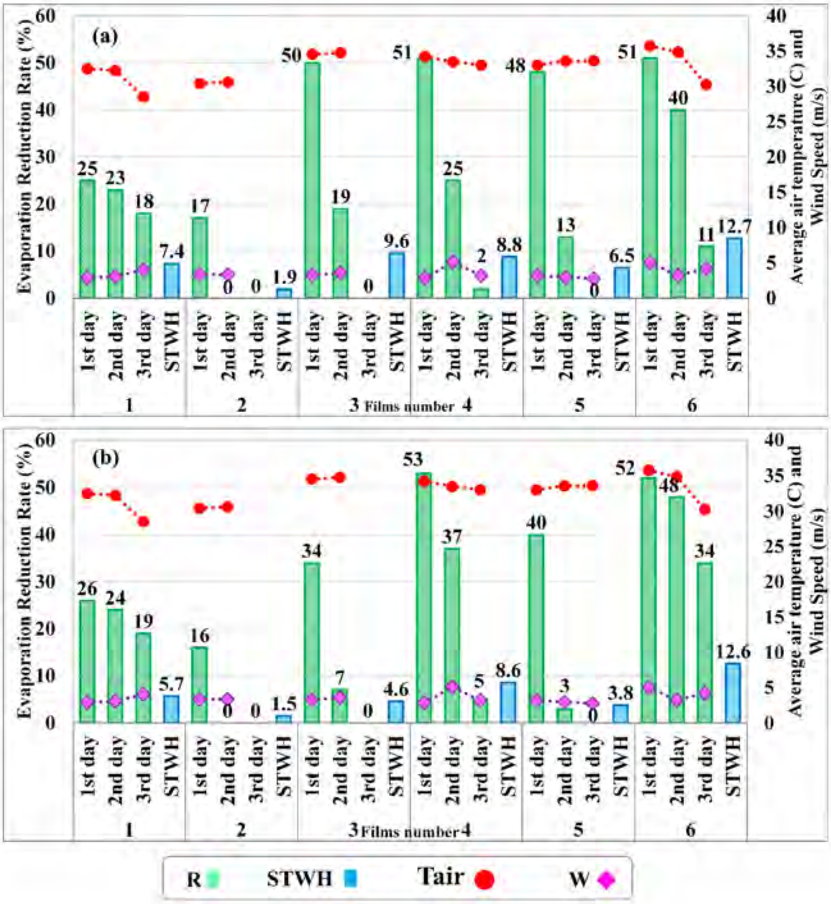

Fig. 3 The films evaporation reduction percentage (R) for the first (1st), second day (2nd) and third day (3rd), Saved Total Water Height (STWH), average air Temperature (Tair) and wind speed (W) for (a) land pans and (b) floating pans

effect on pH, but a decrease in turbidity and TSS in all pans, which was normal due to stagnant water. The average differential values were about 0.2, 1.7 NTU, and 1.2 mg/L for pH, turbidity, and TSS, respectively. Evaporation mitigation films could increase water surface temperature, whose growth rate depends on the functionality of films. For instance, F2 with the least evaporation reduction *R*, showed almost no temperature difference and the best film (F6) showed an average of 5 °C growth, while the overall average for all films was 3.17 °C.

4 Conclusion

The effect of self-assembled nanometric films on the evaporation rate of Chitgar lake was studied from July to August as a period with maximum evaporation throughout the year. The films were composed of cetyl (Ce) and stearyl (St) alcohols along with Jojoba oil (JO), stearic acid (Sa), and calcium hydroxide (CH). In order to investigate their performance, two pairs of Class A evaporation pan were used. One pair was placed on the lake's shore and the other pair was floating on the lake. Results showed that the film consisting of 3:1 St to Ce with 60% by weight of CH had the best performance on both land and floating pans. This film could mitigate evaporation up to 50% and maintain its stability for 72 h in the presence of 5 m/s wind. In our case study of Chitgar Lake, these films showed no significant effect on water quality parameters such as pH, turbidity and TSS. Although this method is a promising way for reducing water evaporation in arid and semi-arid regions with water shortage problems, further studies on biocompatibility and film stability on large scale reservoirs are recommended.

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Data Availability The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

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References

Abbaspour KC, Faramarzi M, Ghasemi SS, Yang H (2009) Assessing the impact of climate change on water resources in Iran. Water Resour Res 45:W10434. https://doi.org/10.1029/2008WR007615

Abtew W, Melesse AM (2013) Evaporation and Evapotranspiration: Measurements and Estimations. Springer Netherlands

Alvarez VM, Baille A, Martínez JMM, González-Real MM (2006) Efficiency of shading materials in reducing evaporation from free water surfaces. Agric Water Manage 84:229–239. https://doi.org/10.1016/j.agwat.2006.02.006

Aminzadeh M, Lehmann P, Or D (2018) Evaporation suppression and energy balance of water reservoirs covered with self-assembling floating elements. Hydrol Earth Syst Sci 22:4015–4032. https://doi.org/10.5194/hess-22-4015-2018

Ardalan A, Khaleghy Rad M, Hadi M (2019) Urban water issues in the megacity of Tehran. Urban Drought: Emerging Water Challenges in Asia. Springer, Singapore, pp 263–288

Ashoori N, Dzombak DA, Small MJ (2017) Identifying water price and population criteria for meeting future urban water demand targets. J Hydrol 555:547–556. https://doi.org/10.1016/j.jhydrol.2017.10.047

Assouline S, Narkis K, Or D (2011) Evaporation suppression from water reservoirs: Efficiency considerations of partial covers. Water Resour Res 47:W07506. https://doi.org/10.1029/2010WR009889

Bagheri M, Kholghi M, Hosseini SM, Amiraslani F, Hoorfar A (2020) Participatory approach in aquifer storage and recovery management in arid zones, does it work? Groundw Sustainable Dev 10:100368. https://doi.org/10.1016/j.gsd.2020.100368

Barnes GT (2008) The potential for monolayers to reduce the evaporation of water from large water storages. Agric Water Manage 95:339–353. https://doi.org/10.1016/j.agwat.2007.12.003

Behrouzi K, Chini F (2016) Estimation of evaporation from Chitgar Lake. U.S.-Iran Symposium on Wetlands. Irvine, California, March;28–30, pp 182–192

Benzaghta MA, Mohammed TA, Ghazali AH, Soom MAM (2013) Testing of evaporation reduction methods in humid climates. Proceedings of the Institution of Civil Engineers - Water Management 166:207–216. https://doi.org/10.1680/wama.11.00053

Boazar M, Yazdanpanah M, Abdeshahi A (2019) Response to water crisis: How do Iranian farmers think about and intent in relation to switching from rice to less water-dependent crops? J Hydrol 570:523–530. https://doi.org/10.1016/j.jhydrol.2019.01.021

Boretti A, Rosa L (2019) Reassessing the projections of the World Water Development Report. NPJ Clean Water 2:1–6. https://doi.org/10.1038/s41545-019-0039-9

Brzozowska AM, Duits MHG, Mugele F (2012) Stability of stearic acid monolayers on Artificial Sea Water. Colloids Surf A 407:38–48. https://doi.org/10.1016/j.colsurfa.2012.04.055

Caruso B, Martini MF, Pickholz M, Perillo MA (2018) V-shaped molecular configuration of wax esters of jojoba oil in a Langmuir film Model. Langmuir 34:7887–7898. https://doi.org/10.1021/acs.langmuir.8b00693

Chang N, Luo L, Wang XC, Song J, Han J, Ao D (2020) A novel index for assessing the water quality of urban landscape lakes based on water transparency. Sci Total Environ 735:139351. https://doi.org/10.1016/j.scitotenv.2020.139351

Craig I, Aravinthan V, Baillie C, Beswick A, Barnes G, Bradbury R, Connell L, Cooper P, Fellows C, Fitzmaurice L, Foley J (2007) Evaporation, seepage and water quality management in storage dams: a review of research methods. Environ Health 7:84–97

Craig I, Green A, Scobie M, Schmidt E (2005) Controlling evaporation loss from water storages. University of Southern Queensland, National Centre for Engineering in Agriculture, Toowoomba, Australia. https://eprints.usq.edu.au/2662. Accessed 30 July 2022

Elkatoury A, Alazba AA, Mossad A (2020) Estimating evapotranspiration using coupled remote sensing and three SEB models in an arid region. Environ Process 7:109–133. https://doi.org/10.1007/s40710-019-00410-w

Farrar LW, Bahaj AS, James P, Anwar A, Amdar N (2022) Floating solar PV to reduce water evaporation in water stressed regions and powering water pumping: Case study Jordan. Energy Conv Manag 260:115598. https://doi.org/10.1016/j.enconman.2022.115598

Finch JW, Hall RL (2006) Evaporation from lakes. In: Encyclopedia of Hydrological Sciences

Fisk PR, Wildey RJ, Girling AE, Sanderson H, Belanger SE, Veenstra G, Nielsen A, Kasai Y, Willing A, Dyer SD, Stanton K (2009) Environmental properties of long chain alcohols. Part 1: Physicochemical, environmental fate and acute aquatic toxicity properties. Ecotoxicol Environ Saf 72:980–995. https://doi.org/10.1016/j.ecoenv.2008.09.025

Fitts CR (2013) 1 - Groundwater: the big picture. In: Fitts CR (ed) Groundwater Science (2nd Edition). Academic Press, Boston, pp 1–22

Fomina ES, Vysotsky YB, Belyaeva EA, Vollhardt D, Fainerman VB, Miller R (2014) On hexagonal orientation of fatty alcohols in monolayers at the air/water interface: quantum-chemical approach. J Phys Chem C 118:4122–4130. https://doi.org/10.1021/jp409911a

Frenken K (2009) Irrigation in the Middle East region in figures: AQUASTAT survey – 2008. Water Reports No.34, Food and Agriculture Organization of the United Nations, Rome https://www.cabdirect.org/cabdirect/abstract/20093247971. Accessed 30 July 2022

Allen RG, Pereira S, Raes L, Smith D M (1998) Crop evapotranspiration - Guidelines for computing crop water requirements. Food and Agriculture Organization of the United Nations, Rome

Gallego-Elvira B, Baille A, Martin-Gorriz B, Maestre-Valero JF, Martínez-Alvarez V (2011) Energy balance and evaporation loss of an irrigation reservoir equipped with a suspended cover in a semiarid climate (south-eastern Spain). Hydrol Process 25:1694–1703. https://doi.org/10.1002/hyp.7929

Gallego-Elvira B, Martínez-Alvarez V, Pittaway P, Brink G, Martín-Gorriz B (2013) Impact of micrometeorological conditions on the efficiency of artificial monolayers in reducing evaporation. Water Resour Manage 27:2251–2266. https://doi.org/10.1007/s11269-013-0286-3

Gooding JJ, Ciampi S (2011) The molecular level modification of surfaces: from self-assembled monolayers to complex molecular assemblies. Chem Soc Rev 40:2704–2718. https://doi.org/10.1039/C0CS00139B

Haghighi E, Madani K, Hoekstra AY (2018) The water footprint of water conservation using shade balls in California. Nat Sustain 1:358–360. https://doi.org/10.1038/s41893-018-0092-2

Haghighi E, Shahraeeni E, Lehmann P, Or D (2013) Evaporation rates across a convective air boundary layer are dominated by diffusion. Water Resour Res 49:1602–1610. https://doi.org/10.1002/wrcr.20166

Hartzell TS (2016) Evaluating potential for floating solar installations on Arizona water management infrastructure, Bachelor's thesis, University of Arizona, Tucson, USA

Hassan MM, Peirson WL (2016) Evaporation mitigation by floating modular devices. IOP Conf Ser: Earth Environ Sci 35:012022. https://doi.org/10.1088/1755-1315/35/1/012022

Hassan MM, Peirson WL, Neyland BM, Fiddis NM (2015) Evaporation mitigation using floating modular devices. J Hydrol 530:742–750. https://doi.org/10.1016/j.jhydrol.2015.10.027

He Y, Wang R, Jiao T, Yan X, Wang M, Zhang L, Bai Z, Zhang Q, Peng Q (2019) Facile preparation of self-assembled layered double hydroxide-based composite dye films as new chemical gas sensors. ACS Sustainable Chem Eng 7:10888–10899. https://doi.org/10.1021/acssuschemeng.9b01780

Hostert JD, Loney CN, Pramounmat N, Yan K, Su Z, Renner JN (2021) Self-assembly and rearrangement of a polyproline II helix peptide on gold. Langmuir 37:6115–6122. https://doi.org/10.1021/acs.langmuir.0c03583

Huang X, Jiao T, Liu Q, Zhang L, Zhou J, Li B, Peng Q (2019) Hierarchical electrospun nanofibers treated by solvent vapor annealing as air filtration mat for high-efficiency PM2.5 capture. Sci China Mater 62:423–436. https://doi.org/10.1007/s40843-018-9320-4

Keeler BL, Wood SA, Polasky S, Kling C, Filstrup CT, Downing JA (2015) Recreational demand for clean water: evidence from geotagged photographs by visitors to lakes. Front Ecol Environ 13:76–81. https://doi.org/10.1890/140124

Khorasani H, Kerachian R, Malakpour-Estalaki S (2018) Developing a comprehensive framework for eutrophication management in off-stream artificial lakes. J Hydrol 562:103–124. https://doi.org/10.1016/j.jhydrol.2018.04.052

Le Dréau Y, Dupuy N, Gaydou V, Joachim J, Kister J (2009) Study of jojoba oil aging by FTIR. Anal Chim Acta 642:163–170. https://doi.org/10.1016/j.aca.2008.12.001

Lee I (2013) Molecular Self-Assembly: Smart design of surface and interface via secondary molecular interactions. Langmuir 29:2476–2489. https://doi.org/10.1021/la304123b

Lendrum C, McGrath KM (2009) The role of subphase chemistry in controlling monolayer behaviour. J Colloid Interface Sci 331:206–213. https://doi.org/10.1016/j.jcis.2008.11.046

Li C-L, Shi K-B, Yan X-J, Jiang C-L (2021) Experimental analysis of water evaporation inhibition of plain reservoirs in inland arid area with light floating balls and floating plates in Xinjiang, China. J Hydrol Eng 26:04020060. https://doi.org/10.1061/(ASCE)HE.1943-5584.0002032

Lombardo D, Kiselev MA, Magazù S, Calandra P (2015) Amphiphiles self-assembly: basic concepts and future perspectives of supramolecular approaches. Adv Condens Matter Phys 2015:e151683. https://doi.org/10.1155/2015/151683

Madani K (2014) Water management in Iran: what is causing the looming crisis? J Environ Stud Sci 4:315–328. https://doi.org/10.1007/s13412-014-0182-z

Martínez-Espinosa RM (2021) Controversy over the use of "shade covers" to avoid water evaporation in water reservoirs. Sustainability 13:11234. https://doi.org/10.3390/su132011234

Matsumoto Y, Ma S, Tominaga T, Yokoyama K, Kitatani K, Horikawa K, Suzuki K (2019) Acute effects of transdermal administration of jojoba oil on lipid metabolism in mice. Medicina 55:594. https://doi.org/10.3390/medicina55090594

Mcjannet D, Cook F, Knight J, Burn S (2008) Evaporation reduction by monolayers: overview, modelling and effectiveness. CSIRO: Water for a Healthy Country National Research Flagship. Urban Water Security Research Alliance. Technical Report, 6:1–32. http://www.urbanwateralliance.org.au/publications/UWSRA-tr6.pdf. Accessed 30 July 2022

Mittal P, Yadav S, Negi S (2021) Advancements for organic thin film transistors: Structures, materials, performance parameters, influencing factors, models, fabrication, reliability and applications. Mater Sci Semiconduct Process 133:105975. https://doi.org/10.1016/j.mssp.2021.105975

Mohammadi M, Safaie A, Nejatian A, Iraji zad A, Tajrishy M (2022) Lake Urmia water evaporation suppression using self-assembled coating: case study of pools near the lake. J Hydrol Eng 27:05022001. https://doi.org/10.1061/(ASCE)HE.1943-5584.0002162

Motlaghzadeh K, Kerachian R, Tavvafi A (2020) An evidential reasoning-based leader-follower game for hierarchical multi-agent decision making under uncertainty. J Hydrol 591:125294. https://doi.org/10.1016/j.jhydrol.2020.125294

Mozafari A, Mansouri B, Chini SF (2019) Effect of wind flow and solar radiation on functionality of water evaporation suppression monolayers. Water Resour Manage 33:3513–3522. https://doi.org/10.1007/s11269-019-02313-9

Oroud IM (2015) Water budget assessment within a typical semiarid watershed in the eastern Mediterranean. Environ Process 2:395–409. https://doi.org/10.1007/s40710-015-0072-8

Pittaway P, van den Ancker T (2010) Microbial and environmental implications for use of monolayers to reduce evaporative loss from water storages. CRC for Irrigation Futures, Toowoomba, Australia. Technical Report No. 07/10. https://core.ac.uk/download/pdf/11050327.pdf. Accessed 30 July 2022

Pittaway P, Herzig M, Stuckey N, Larsen K (2015) Biodegradation of artificial monolayers applied to water storages to reduce evaporative loss. Water Sci Technol 72:1334–1340. https://doi.org/10.2166/wst.2015.348

Pouladi P, Nazemi AR, Pouladi M, Nikraftar Z, Mohammadi M, Yousefi P, David JY, Afshar A, Aubeneau A, Sivapalan M (2022) Desiccation of a saline lake as a lock-in phenomenon: A socio-hydrological perspective. Sci Total Environ 811:152347. https://doi.org/10.1016/j.scitotenv.2021.152347

Prime EL, Tran DNH, Plazzer M, Sunartio D, Leung AH, Yiapanis G, Baoukina S, Yarovsky I, Qiao GG, Solomon DH (2012) Rational design of monolayers for improved water evaporation mitigation. Colloids Surf A 415:47–58. https://doi.org/10.1016/j.colsurfa.2012.09.025

Ravanshadnia M, Ghanbari M, Fardani MH (2015) Planning crisis management of water resources in Tehran in the next twenty-five years. J Appl Environ Biol Sci 5(10):50–59

Rudra JS, Kelly SH, Collier JH (2017) 2.4 Self-assembling biomaterials. In: Ducheyne P (ed) Comprehensive Biomaterials II. Elsevier, Oxford, pp 67–89

Saggaï S, Bachi OEK (2018) Evaporation reduction from water reservoirs in arid lands using monolayers: Algerian Experience. Water Resour 45:280–288. https://doi.org/10.1134/S009780781802015X

Sánchez M, Avhad MR, Marchetti JM, Martínez M, Aracil J (2016) Jojoba oil: A state of the art review and future prospects. Energy Conv Manag 129:293–304. https://doi.org/10.1016/j.enconman.2016.10.038

Sánchez M, Marchetti JM, El Boulifi N, Aracil J, Martínez M (2015) Kinetics of Jojoba oil methanolysis using a waste from fish industry as catalyst. Chem Eng J 262:640–647. https://doi.org/10.1016/j.cej.2014.09.088

Sebbar A, Heddam S, Djemili L (2019) Predicting daily pan evaporation (epan) from dam reservoirs in the Mediterranean regions of Algeria: OPELM vs OSELM. Environ Process 6:309–319. https://doi.org/10.1007/s40710-019-00353-2

Shahraeeni E, Lehmann P, Or D (2012) Coupling of evaporative fluxes from drying porous surfaces with air boundary layer: Characteristics of evaporation from discrete pores. Water Resour Res 48:W09525. https://doi.org/10.1029/2012WR011857

Simon K, Shanbhag R, Slocum AH (2016) Reducing evaporative water losses from irrigation ponds through the reuse of polyethylene terephthalate bottles. J Irrig Drain Eng 142:06015005. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000972

Skardi MJE, Kerachian R, Abdolhay A (2020) Water and treated wastewater allocation in urban areas considering social attachments. J Hydrol 585:124757. https://doi.org/10.1016/j.jhydrol.2020.124757

STPCEC (Sadd Tunnel Pars Consulting Engineering Company) (2012) Studies of the construction of Chitgar Artificial Lake. Tehran, Iran, Technical Report (in Persian)

Wang R, Yan X, Ge B, Zhou J, Wang M, Zhang L, Jiao T (2020) Facile preparation of self-assembled black phosphorus-dye composite films for chemical gas sensors and surface-enhanced raman scattering performances. ACS Sustainable Chem Eng 8:4521–4536. https://doi.org/10.1021/acssuschemeng.9b07840

WMO (2008) Guide to meteorological instruments and methods of observation (WMO-No. 8). World Meteorological Organization, Geneva 2, Switzerland

Yan K, Yuan Z, Goldberg S, Gao W, Ostermann A, Xu J, Zhang F, Elser J (2019) Phosphorus mitigation remains critical in water protection: A review and meta-analysis from one of China's most eutrophicated lakes. Sci Total Environ 689:1336–1347. https://doi.org/10.1016/j.scitotenv.2019.06.302

Yao X, Zhang H, Lemckert C, Brook A, Schouten P(2010) Evaporation reduction by suspended and floating covers: Overview, modeling, and efficiency. Urban water security research alliance technical report, 28:1–13. http://www.urbanwateralliance.org.au/publications/uwsra-tr28.pdf. Accessed 30 July 2022

Yazdanpanah M, Hayati D, Zamani GH, Karbalaee F, Hochrainer-Stigler S (2013) Water management from tradition to second modernity: an analysis of the water crisis in Iran. Environ Dev Sustain 15:1605–1621. https://doi.org/10.1007/s10668-013-9452-2

Zhen Z, Xi TF, Zheng YF (2015) 11 - Surface modification by natural biopolymer coatings on magnesium alloys for biomedical applications. In: Narayanan TSNS, Park I-S, Lee M-H (eds) Surface Modification of Magnesium and its Alloys for Biomedical Applications. Woodhead Publishing, pp 301–333

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