Response to Reviewer # 2 Comments (manuscript # hess-2017-415):

"Evaporation suppression and energy balance of water reservoirs covered with self-assembling floating elements"

Milad Aminzadeh, Peter Lehmann, and Dani Or

Dear Editor,

We greatly appreciate the constructive and insightful comments made by reviewer # 2. In the following, we address the comments and concerns raised by the reviewer.

Reviewer comment: *This is a well written and presented article. It provides a relatively simple but surprisingly comprehensive theoretical and physical basis of evaporation suppression from simple, shallow reservoirs from which more detailed work can emerge. It does this by comparing models of an uncovered reservoir to ones covered by white and black circular discs. A 1-D, column approach was used. I wondered why triangular covers were not considered as they have the potential of having no gaps between them (or much smaller ones than a disc).*

Reply: We thank the reviewer for the efforts and for the many insightful comments. As mentioned in Page 10 (L 10-16), the aerodynamic resistance for vapor flux from water gaps forming between cover elements is governed by the combined effects of gap size (a_g), boundary layer thickness (δ) and the lateral spacing between neighboring gaps. For very small gaps formed by polygonal covers, gap sizes could become smaller than the boundary layer thickness (the ratio of a_g/δ smaller than 1). This case may yield evaporation enhancement disproportional to size of the gap according to Eq. (13) [Schlunder, 1988; Shahraeeni et al., 2012]. In addition, for certain applications of multiuse reservoirs, water gaps formed between spherical or cylindrical covers allow light penetration and provide surfaces oxygen transfer both play important roles in ecological aspects of the water body.

Reviewer comment: *The paper could be well served by articulating right at the outset the methodology you use. This is how I perceive it (from reading p. 11): 1. Calculation of evaporation reduction due to discs; 2. Effect of heat balance of the discs on water column, the primary evaporation reduction element; 3. Effect of heat balance of the gaps between discs on water column, including conduction from disc to water; 4. Effect of the increase of gap water surface temperature due to 2 and 3.*

Reply: We thank the reviewer for the suggestion and we will provide a summary of the main steps and methodology in the revised manuscript.

Reviewer comment: *Advection of (likely) colder water into the column was brought up in a discussion of managed input vs output for the reservoir but non-advective heat transfer was only considered for the bottom of the column. What about the four sides (can assume a simple soil temperature profile)?*

Reply: Clearly, for small reservoirs lateral heat exchange with the water body could be important in the energy balance. At this stage we seek to establish a simple 1-D model for reservoirs where vertical temperature profile and surface heat fluxes dominate the response in the presence of floating elements, we thus neglect lateral heat transfers of the reservoir assuming that the side area of the reservoir is small relative to its depth (as is likely in many shallow reservoirs). Following this comment, we will explicitly mention this simplification in the revised manuscript (to also consider this aspect in applications to small ponds).

Reviewer comment: *The diffusivity coefficient, D, did not appear to include any internal dynamics such as non-linear and/or breaking waves, which would likely increase it. The authors might consider such inclusion for completeness. Although, I must admit, internal motions in such a shallow reservoir would not be very large or complex. However, I am not aware of any observations of internal motions in shallow reservoirs and there are few for larger, deeper ones (with bottom topography forcing the wave motion). Managed releases would exacerbate wave activity.*

Reply: We note that some of the internal motions in deep reservoirs are attributed to the onset of thermal instabilities as included in the model representation (Eq. 10); additionally, effects of wind friction velocity are explicit in the (nonlinear) formulation of the eddy diffusivity in Eq. (3). Clearly, inflows-outflows, bottom topography, and breaking waves would enhance mixing and thus modify effective eddy diffusivity. However, keeping with the simple 1-D formulation of Henderson-Seller [1985], we retain surface interactions of eddy diffusivity with wind (that is likely to be altered in the presence of the floating cover!). Following the reviewer comment, we will explain these aspects in the revised manuscript.

Reviewer comment: *It appeared implicitly assumed that the water was not turbid, a rare condition in most reservoirs. A short discussion of the effect of turbidity on the columnar distribution of heat would enhance the work and provide an avenue for further theoretical work.*

Reply: We thank the reviewer for raising this point; we have considered parameterization of light penetration and various radiative effects in Eq. (2), but we will add a short discussion of this aspect in the revised manuscript (with common values and ramifications).

Reviewer comment: *While the amount of open water subject to heating is small in this study, for completeness at least a nod to the Clausius-Clapeyron relationship should be noted (and, I guess, dismissed). It had a major impact on the "failure" of monomolecular layer cover evaporation suppression in the famous Lake Hefner (Oklahoma, USA) Evaporation Reduction Experiment in 1967 (Bean and Florey, 1968, Water Resources Res., 4, 206- 208; also notes an evaporation reduction of about 60%) because the water warmed up when evaporation was reduced. Wind removed the layer, exposing the warm water, which then had higher evaporation due to the warmer water resulting in a net loss.*

Reply: We thank the reviewer for raising this important point. We include the Clausius-Clapeyron relationship in the representation of evaporative flux based on the "saturated vapor concentration" that is a function of surface temperature (e.g., see Eq. 8). The difference from the cases mentioned, is with the energy balance over the covers either via albedo reflection (white covers) or sensible heat exchange (black covers) with minimal net heat flux to the surface (laboratory experiments). We will add a discussion of the potential nonlinear evaporation enhancement effects as a function of surface water temperature.

Reviewer comment: *An important metric, the mean depth, $D = V/A$, where V is the reservoir volume and A, its surface area was not discussed. An efficient reservoir would be one where V is large and A is small resulting in a large value of D; in other words a cylinder will evaporate less than a bowl of the same volume. In this case $3m < D < 10m$ was considered. This is very shallow, implying a rapid response of reservoir heat content to varying atmospheric forcing; in other words the surface temperature, the main driver of the evaporative process, responds rapidly to latent and sensible heat* *transfer as well as the mean temperature of the volume. There is little phase lag between the near surface heat balance and interior heat balance; both will closely follow the daily average air temperature and net radiation input.*

In a deeper reservoir, Lake Mead was used where D is 165, there is a considerable phase lag in the diurnal and seasonal variations of surface versus interior temperature. For instance, in summer daytime air temperature will likely exceed the water temperature; a stable situation resulting in reduced evaporation especially in windless conditions. The reverse is true at night, when water temperatures are likely warmer than air temperature. Since during summer mid-latitude daylight hours substantially exceed nighttime hours so the lower evaporation during the day will dominate. In Fall, surface temperature will decrease due to lower insolation amount and duration, but will this will likely be mitigated by heat transfer into the surface layer by relatively warmer water in the interior resulting in relatively warmer surface temperature than air temperature throughout the day resulting in potentially more evaporation in that season (and Winter) compared to summer. The results shown in this article do not support this heuristic argument. However, eddy correlation observations over a period of years over Lake Superior (Blanken, P. et al., 2011, J. Great Lakes Res., 37, 707-716) show this nicely.

Reply: We note that the present model was developed with relatively shallow reservoirs in mind (i.e., depth<10 m). As pointed out by the reviewer, the response of such shallow reservoirs to atmospheric condition is rapid and the time lag between surface and interior heat balances is relatively short. A comparison with data from Lake Mead (a relatively deep reservoir), enabled testing of key aspects of the model towards establishing a reference uncovered surface for evaluating effects of floating covers on the energy balance (the main objective of the present study). We agree with the reviewer that in the presence of phase lags and multiple mixing (e.g., dimictic reservoirs), the evaporative flux could be affected and even leading to enhanced evaporative losses during the winter. We point out however, that the monthly evaporation data from Lake Mead support the results of higher evaporative losses during summer even for such a deep reservoir (the Figure A below). We will add a discussion of the subject (and potential deviations from the assumptions) in the revised manuscript.

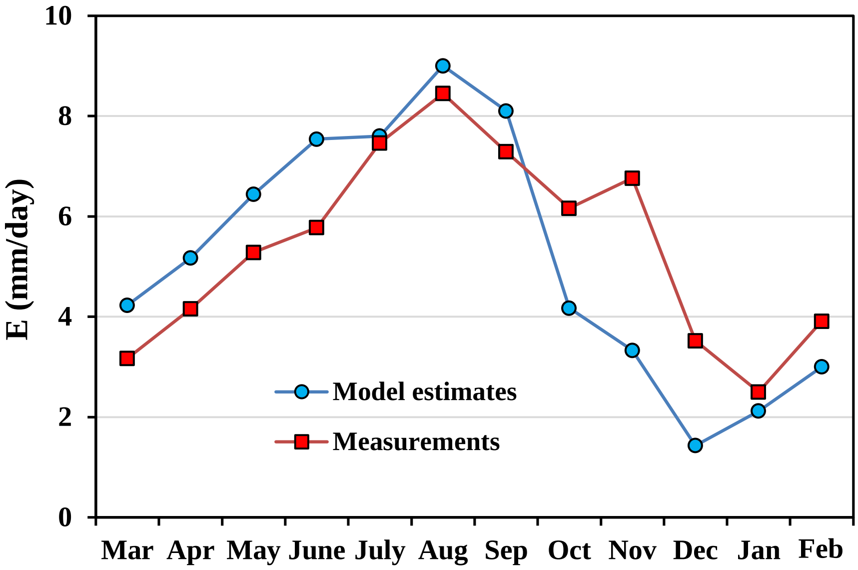

Figure A. Comparing model estimations of evaporative loss from Lake Mead with measurements demonstrating that evaporative losses during summer are dominant.

Reviewer comment: *Last, I recall talking with a farmer who was the leader of a ditch company that managed a small reservoir as assumed here. He was very interested in estimating evaporation and, of course, suppressing it with some sort of cover as described here. I asked him if he had planted a wind break on the windward side. He was stunned and said he had not thought of it. So I said: "But you thought of it for your fields and that isn't open water. Furthermore, it would be a good use of otherwise "lost" leakage to ground water." So while I understand this windbreak approach and the consideration of internal boundary layers formed by changes in surface friction is not conducive to such a study as outlined here, I feel a theoretical approach to these aspects of real world reservoirs would be worthwhile in the search for low-impact geoengineering of simple reservoirs. This group obviously has the tools and expertise.*

Reply: We thank the reviewer for sharing these insights; we also consider aspects of internal boundary layer and its impact on local heat and mass transfer processes key to the efficiency of the cover. We thus plan to further investigate such nuanced aspects in the next steps of this ongoing project to provide a comprehensive framework, including both physical and ecological aspects for design and management of (optimal) floating elements.

Minor comments

- *p. 2, l. 15: I believe the recent use of black balls in a Los Angeles reservoir was not aimed at evaporation reduction but the reduction of toxic algae blooms. I think Israeli engineers have used white ping-pong like balls to reduce evaporation in test reservoirs (don't have a reference).*

  Reply: The reviewer is right, the initial motivation was suppression of photochemical reactions and evaporation suppression from Los Angeles reservoirs was a secondary goal. Nevertheless, the water saving aspect gained prominence with the lingering drought in California (as reflected in highly publicized media cover: https://www.engadget.com/2016/09/21/the-big-picture-shade-balls-los-angeles-reservoir/)

- *p. 7, eq. 6a: Please check for references for some of these empirical relationships. Some equations are referenced, some not.*

  Reply: As mentioned in Page 6, L 9, Eq. (3) and subsequent equations used for quantification of eddy thermal diffusivity are provided by Henderson-Seller [1985]. Following the comment of the reviewer, we will explicitly point it in the revised manuscript.

- *p. 7, eq. 6b: some readers will not recognize the Brundt-Viasala relationship, which carries some restrictive assumptions with it. Interestingly on a windless or low wind day, this might be more likely during the day and convective mixing, as noted in this work, which is more likely at night when surface temperature might be lower than temperatures below.*

  Reply: We thank the reviewer for the comment; the Brunt-Viasala relation is part of the stability parameterization of the eddy thermal diffusivity by Henderson-Seller [1985] and plays an important role in the water mixing we consider in this work.

- *p. 7, l. 12-13: Do you have a reference for the assumption?*

  Reply: The assumption arises from the continuity of temperature profile at the interface of liquid and solid phases. We will provide appropriate references in the revised manuscript.

- *p. 8, eq. 8: explain why you use C for vapor concentration instead of the more recognizable q, specific humidity.*

  Reply: The representation based on the vapor concentration arises from Fickian mass transfer across the air boundary layer (implying dominance of diffusive fluxes [Haghighi et al., 2012]). In any case, we don't expect this to affect the clarity of the analysis as vapor concentration and specific humidity are linked via air density (we will add a comment for the readers more comfortable with q).

- *p. 8, l. 15, Fig. 2: is this the heavy dashed line in the Figure? It needs to be explained.*

  Reply: It is represented by the solid line denoted as T_m, we will remove the heavy dashed line in the revised manuscript to avoid confusion of the readers.

- *p. 10, l. 13-14: jargon alert! "three-dimensional vapor shells" Show or explain further. Also what is meant by "lateral spacing"? Perhaps you can show these in Fig. 3b.*

  Reply: The reviewer is right to "alert" of such jargon use. The point here is that for small lateral spacing between neighboring water gaps in the cover (either for covers made up of small elements, or densely punctured plastic cover), the vapor concentration profile resulting over the surface is nearly 1-D and layered (left image below); as spacing increases, the vapor profiles form individual 3-D domes that act to enhance evaporative flux from individual gaps. This is schematically represented in the image below. Following the reviewer comment, we will explain it better in the revised manuscript.

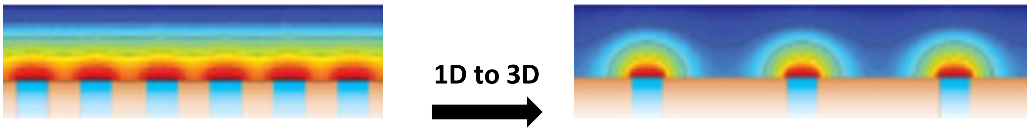

Figure B. Conceptual image of evolution of vapor shells above individual water gaps with increasing spacing between them.

- *p. 12, l. 12: Consider "Given the simplifying assumptions, the model overestimates: : :.".*

  Reply: Thanks, we will amend the sentence in the revised manuscript.

- *P. 13, Fig. 5: Comment on the slow uptake of heat in Spring (cold water/warm air) vs rapid decrease in Fall (warm water/cold air) to add confidence in the model. You might find observational evidence to back up a heuristic argument: surface layer more stable in Spring, more convective in Fall.*

  Reply: We appreciate this constructive comment and will provide further discussions on the evolution of temperature profile in the revised manuscript.

- *p. 13, l. 18-19 "..demonstrate : : : a much colder reservoir." This is an impressive modeling result and should be tested by a field experiment. Is one being considered?*

  Reply: We are aware that model predictions require confirmation using reservoir scale experiments that are currently unavailable. We note that a colder water body under floating elements was observed in our preliminary lab scale measurements in a small basin ($1.2\times1.2\times0.16$ m^3), and are presently conducting two field scale measurements (in EAWAG

(Switzerland) and Isfahan University of Technology (Iran); see images) to provide the necessary data for model evaluation.

Figure C. Ongoing “field scale” experiments conducted in EAWAG near Zurich using 8 ponds each 14 m^2 and 1.5 m deep covered with white and black 0.2 m (EVA foam) floating covers including two uncovered control ponds

- *p. 17, Section 3.3, Ecological considerations: Reservoirs, even small, simple ones as assumed here, while not likely used for recreation, can be important to migratory birds and other wildlife as well as aquatic life in the reservoir (which often provide food for wildlife visiting the reservoir, extending the ecological boundary). Discs, as described here, will inhibit access for wildlife. That should at least be mentioned along with the impossibility of modeling it. Although, for any future work, you might consider entraining a wildlife expert who might.*

  Reply: The reviewer is right, ecological aspects of covered reservoirs are not limited to aquatic organisms only and additional aspects including birds and wildlife should be considered. Future development of the framework will consider other more nuanced ecological aspects such as optimizing surface coverage to provide required light and oxygen for aquatic life and accessibility to other organisms as pointed out.

- *p. 18, Section 3.4, Costs and water savings: A nice summary. Have an economist vet it, if you haven’t. I especially liked the last sentence. You might mention water scarcity as a conflict enhancer as described recently by Tom Friedman, a well-known columnist for the New York Times. So efficient storage of water becomes political.*

  Reply: We thank the reviewer for raising this point and will further discuss (the rapidly evolving) economics of water saving in the revised manuscript and in follow up studies.

- *p. 22, l. 10-18: You should mention an important effect of the discs I did not see in the paper but suggested in this discussion; the appearance of waves, breaking waves, and spray as wind increases (threshold _ 6 mps). This radically changes the situation in open, uncovered water and greatly increases the evaporation; modeling this effect is still elusive though a check of hurricane boundary layer modeling may provide some insights.*

  Reply: We will discuss the impact of discs on surface waves, shear velocity and potential impacts on the evaporative loss in the revised manuscript (albeit this will be done in a generic fashion due to lack of data and much larger scope than the present study).

- *P. 23, Eq. B3: Is this correct? Should it be $\lambda = D/H$ to be dimensionless as described later in the Appendix?*

Reply: Please note that the dimension of *d.H* is m^2 and the parameter *N* represents number of discs per unit "area" rendering λ a dimensionless parameter ($\lambda = N\, d\, H$).

- *p. 24, l. 13-15: 3 to 10 m is not enough depth variation. Note that Rn, H, and E are essentially constant and heat storage decreased by 27% for the 10 m depth. Can you show the "index" Ta – Tw for the two depths? I predict they will be nearly the same.*

Reply: Note that the focus of the present study is on shallow reservoirs often used for seasonal water storage for domestic, agricultural or industrial use in dry periods. The similarity of surface heat fluxes between shallow and deep scenarios is associated with similar surface temperatures and the effect of depth is thus reflected in specific storage and bottom fluxes. Following the reviewers comment, the following plot depicts the difference between air temperature and mean vertical temperature of the reservoir. Although they look similar, the differences in summer and winter are of the order of 3^{o}C.

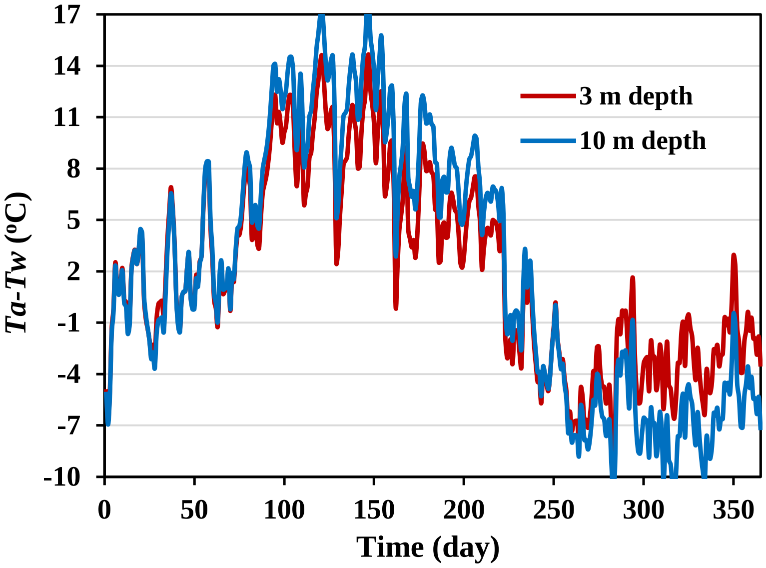

Figure D. Variation of T_a-T_w for shallow and deep reservoirs. The water temperature (T_w) represents the mean vertical temperature of each day.

- *Figure 1: I'd replace that with a Google Earth picture of the Front Range (eastward) of Colorado which is dotted with small reservoirs to show how ubiquitous they are. Using the area tool on the USGS National Map Viewer you could show that the combined area of these "small" reservoirs approximate that of major reservoirs in the Colorado River Basin system.*

Reply: Thanks for the suggestion; we will consider using the map of the suggested area in the revised manuscript.

- *Figure 2: Those two hatched areas do not look equal to me. Explain the dashed line.*

Reply: Considering Eq. (10), the hatched areas on the left and right hand sides of T_m are the same. As mentioned earlier, we will remove dashed line in the revised manuscript to avoid confusion of potential readers.

- *Figure 3: What is the red triangle on the far left side? You've labeled the down arrows to the far left and right, what is the label for the one between them? What does the expression below fc represent?*

Reply: As expressed in the caption of Figure 3, the red triangle with side lengths equal to the disc diameter marks a unit cell that enables calculation of surface coverage based on the geometry as 0.91. The arrow between the down arrows is q_c; we will add it to the revised Figure. The expression indicates attenuation of radiative flux in depth; we will better highlight it in the revised manuscript.

- *Figure 4: "assumed"? Be honest, wasn't it "tuned"? Were "η" and "β" observed?*

  Reply: To obtain the radiative properties and light attenuation in Lake Mead, we already contacted Dr. Michael Moreo at USGS who is responsible for measurements at the lake; his reply was "*I do not have any subsurface radiation attenuation data. I will say the lake is very clear, and I suspect that radiation penetration is as deep as other very clear lakes*". We thereby estimated the values of η and β based on the literature data reported for clear water bodies.

- *Figure 7: I think 7c is a result of the shallowness of the reservoirs you are modeling. They are like an evaporation pan which has a similar trace with respect to season. Deeper reservoirs show a maximum in Fall/Winter and a minimum in Summer for good reasons. Dew forms on the surface of Lake Superior in summer!! I've witnessed explosive evaporation events associated with reservoir overturning in mid-winter with air temperature of -12C.*

  Reply: Please note that higher evaporative loss during winter is not general as observation in Lake Mead indicates higher evaporation during summer (please see Figure A above). Considering the reviewer's comment, we thus recall that the focus of the present work is on relatively shallow reservoirs whereby evolution of surface fluxes are expected to follow seasonal cycles with higher evaporative loss in summer.

We thank again the reviewer for many helpful comments and hope the Editor finds the clarifications satisfactory.

Sincerely,
Milad Aminzadeh, Peter Lehmann, and Dani Or