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The Seawater Greenhouse in the United Arab Emirates: thermal modelling and evaluation of design options

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Abstract

The Seawater Greenhouse combines a solar desalination system with an environment for cultivating crops in which transpiration is minimised. Results from the prototype greenhouse in the United Arab Emirates (UAE) are used to calibrate a computational fluid dynamic (CFD) model. With the UAE design taken as a baseline, the model is used to evaluate three proposed options for improving performance. These differ with respect to how the plants are shaded and how air flows through the greenhouse. In the baseline design, a semi-opaque plastic sheet is used to provide shade. The first option uses a similar sheet; however the air flows in a C-shaped path, travelling in opposite directions above and below the sheet. The second option uses a perforated sheet through which air is drawn. In the third option, an array of plastic pipes carrying seawater provides shade. The warmed seawater from the pipes is fed into the back evaporator to boost fresh water production. We present results for freshwater production, evapotranspiration and temperatures inside the greenhouse, covering a range of ventilation airflows. The first option gives only marginal improvements in freshwater production and cooling. In contrast, the second option significantly increases water production. Air temperature in the greenhouse increases, whereas the mean radiant temperature decreases. The third option gives the greatest increase in water production in addition to slightly lower air temperature in the greenhouse and significantly lower mean radiant temperature. Evapotranspiration varied little over all the cases studied. The reasons for these findings and their implications for the design of the system are discussed.

Keywords: Solar distillation; Greenhouse desalination; Irrigation; Humidification-dehumidification

1. Introduction

Currently agriculture accounts for around 70% of all human water use. In arid countries, this figure can exceed 90%. Scarcity of water is very detrimental to agriculture and it is expected that growth in world population will aggravate the situation further [1]. In the context of desalination it is therefore relevant to consider technologies

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that will facilitate more efficient water use in agriculture.

The Seawater Greenhouse provides an environment in which the transpiration loss from plants is minimised, at the same time producing sufficient water for its own use through a process of solar distillation.

Goosen et al. [2] have recently reviewed a number of solar distillation approaches, focussing on those involving humidification and dehumidification of air. They point out that, whereas these processes have existed for a long time, their combination with growth of crops in a greenhouse is relatively new and has a significant effect on the process economics.

Indeed, solar distillation projects have been demonstrated in several locations around the world [3,4]. In some cases, projects were decommissioned because they were judged uneconomic to maintain.

There are a number of ways in which the integration of a solar distillation plant with a greenhouse could save costs and lead to more favourable economics. For example, certain components of a solar still such as the glazing and the base are provided for by the cladding and foundation of the greenhouse. In addition, there are a number of indirect cost savings that may be less obvious. Solar distillation plants tend to occupy substantial areas of land and this implies overheads such as securing the site, providing access roads and general services. It is, however, normal to find such infrastructure on a greenhouse site.

In this article we focus on some fundamental aspects of the design of the Seawater Greenhouse, concerning the airflow and shading inside the planting area. The greenhouse is required to provide a relatively cool and humid environment for the cultivation of a variety of crop species thus avoiding water or heat stress. At the same time it must deliver hot fluid to the distillation stage of the process. Careful design is required to avoid conflict arising between these requirements.

2. Description of system

We wish to evaluate some proposed designs options against the baseline provided by the prototype constructed in the United Arab Emirates in 2000, illustrated in Fig. 1.

The main structure of this prototype consists of a series of steel hoops clad with polythene. At the front of the building (on the right in Fig. 1) air enters through an evaporative cooling pad. Close to the back of the building, the air exits through a second evaporative cooling pad and enters a tube-and-fin condenser where freshwater is produced. The condenser is supplied with cooled seawater from the front evaporative cooling pad.

Plants are grown in the area between the front

Fig. 1. The Seawater Greenhouse in the United Arab Emirates.

and back evaporator, referred to as the growing area. This measures 18 m wide by 42 m long giving 756 m^2. Approximately 2 m above the ground, sheets of selectively absorbent polythene are suspended to provide additional shading. The sheet covers most of the growing area however there are gaps at the front and back of the greenhouse.

A data logging system (Delta-T devices, Burwell, UK) provided continuous monitoring of ambient and internal conditions over the period of the study.

The main parameters relating to this greenhouse are summarised in Table 1.

Table 1
Main design parameters for the prototype Seawater Greenhouse, UAE, which serves as the baseline for this study

Width, m	18
Length of planting area, m	42
Maximum height, m	5.5
Air flow, m^3/s	15
Dimensions (width × height × thickness):	
Front evaporator, m	12×2×0.2
Back evaporator, m	8×2×0.2
Condenser, m	4×1.8×0.15

3. Model calibration

Early attempts to model the greenhouse used lumped parameters and one-dimensional networks of control volumes connected by flows of air and water. Eventually these simple models became exhausted in their ability to explain observations taken from the real greenhouse. Therefore it was decided to progress to a computational fluid dynamic (CFD) model, based on the standard software package Flovent 4.2 (Flomerics Ltd, Hampton Court, UK) which is intended specifically for the design and optimization of airflow in buildings.

For the purpose of verifying the model, temperatures were measured at two points in the UAE greenhouse: (i) at the centre of the planting area, 0.5 m above the ground, and (ii) at the outlet of the planting area, near the roof, where the air is about to enter the back evaporator pad. Outside the greenhouse ambient solar radiation, dry and wet-bulb temperatures were monitored. The speed of the fans used to ventilate the greenhouse was monitored and used to deduce the ventilation airflow rate. The rate of water production was also monitored.

The model was verified for a series of readings taken at solar noon over a 14-d period. The conditions are summarised in Table 2.

The main design features of the greenhouse were modelled in the CFD program. The solar inputs were represented as sources spread evenly over the shade screen and the floor of the greenhouse.

During the period of the study, there was no significant planting in the greenhouse and therefore plants were not included in the model. However, the water produced was used to irrigate the soil and the consequent heat absorption due to evaporation was taken into account as a heat sink spread over the floor of the greenhouse.

Radiation heat transfer effects were included in the model. The polythene cladding of the greenhouse transmits long-wave infrared radiation. For the purpose of calculating losses to the sky, the background temperature was set to 294 K [5]. The flow was modelled as 3-dimensional and turbulent using the LVEL k-epsilon model.

The model was used to calculate flow fields and temperature distributions. Monitor points were defined corresponding to the centre and outlet measurement points. The model reported

Table 2
Range of main variables over the 14-d study (9"22 March 2001)

Parameter	Min	Max
Solar radiation, W/m^2	197	849
Watering rate, l/min	0	1.46
Ventilation rate, m^3/s	8.0	11.3
Ambient dry bulb temp., ºC	25.3	37.2
Ambient wet bulb temp., ºC	20.6	24.7

both air and mean radiant temperatures at each of these points.

Fig. 2a compares the modelled result of air temperature with measurements taken at the outlet of the greenhouse. Good agreement is observed. The mean radiant temperature is shown on the same graph.

Fig. 3 indicates the flow field on a longitudinal cross section through the greenhouse. A feature that stands out is the tendency of air to recirculate, with a reversal of direction near the roof. Further analysis showed that recirculatory convection cells could similarly occur on a transverse section through the greenhouse. This suggests a certain amount of mixing of air in the greenhouse, which will tend to reduce spatial differences in temperature.

Fig. 4 indicates the mean radiant temperature field throughout the planting area. It shows that long-wave radiation from the floor and shade screen of the greenhouse is substantial in the centre of the planting area. Thus in Fig. 2b we see that the model reports values of mean radiant temperature up to 13°C above air temperatures. The measured temperatures tend to lie between the two sets of values.

4. Design options

The model calibration exercise confirmed that it is possible to produce useful predictions of temperatures and airflow in the Seawater Greenhouse in the UAE. It showed that the net result of recirculation and radiation effects was to reduce

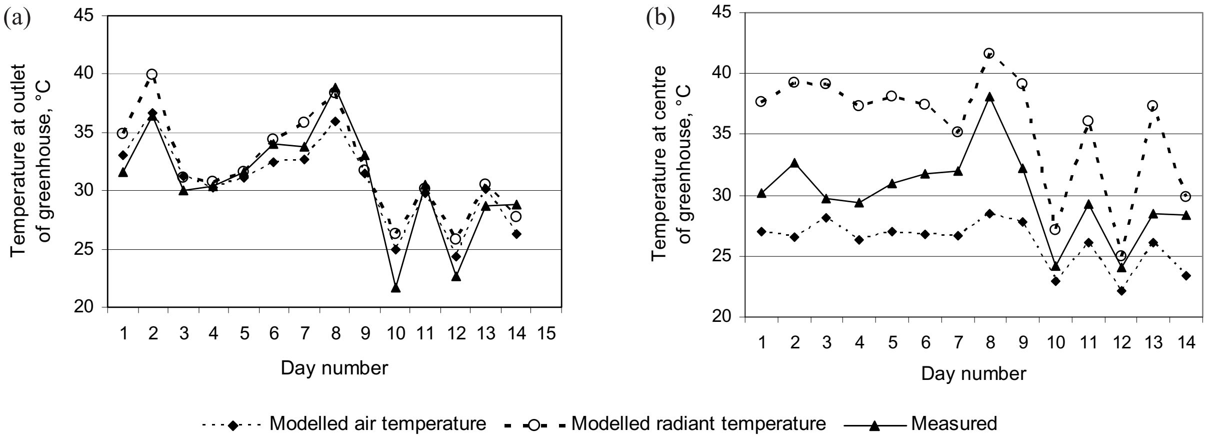

Fig. 2. Modelled air temperature, and modelled mean radiant temperature and measured temperature (a) at the air outlet of the planting area, (b) at the centre of the planting area of the greenhouse.

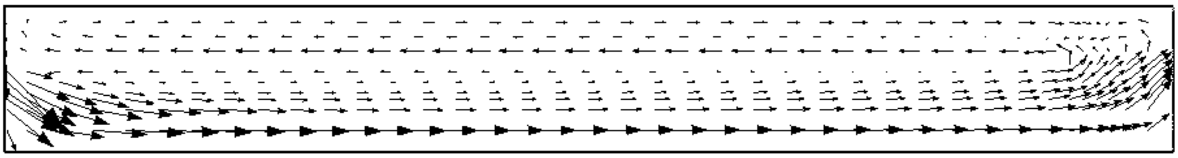

Fig. 3. Velocity field from the CFD model of the greenhouse in the United Arab Emirates, shown on a vertical plane along the centreline of the greenhouse. The main direction of flow is from left to right, however some flow occurs in the opposite direction near the roof.

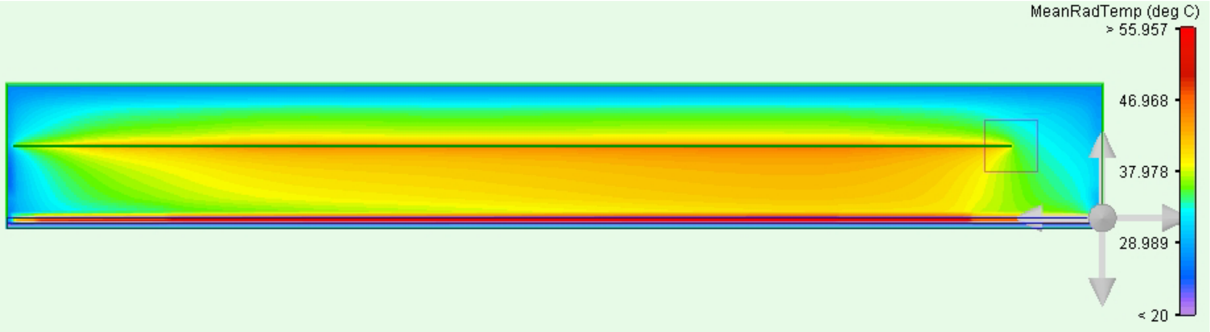

Fig. 4. Distribution of mean radiant temperature inside the greenhouse in the United Arab Emirates, shown on a vertical plane along the centreline of the greenhouse. The main air flow direction is from left to right.

the measured temperature difference from the centre of the planting area to the outlet.

The performance of the system could be improved if the temperature in the centre of the planting area were reduced while the outlet temperature (and therefore rate of freshwater production) is maintained or increased.

To this end three options were considered:

(i) In the first option, shown in Fig. 5a, the air is forced to flow in a C-shaped path, first below the shade screen and then above it. This is intended to force the air to flow along a long, narrow path and therefore reduce recirculation and mixing between inlet and outlet.

(ii) The second option (see Fig. 5b) aims specifically to overcome the issue of high mean radiant temperature by reducing the surface temperature of the shade screen. The heat transfer from the shade screen to the surrounding air is increased by using a perforated screen and forcibly drawing air through the screen. It is thus possible to enhance several-fold the heat transfer, relative to an imperforated horizontal sheet [6]. To establish the limit of the benefit that can be gained from this approach, we model the sheet as being in thermal equilibrium with the surrounding air.

(iii) The third option (see Fig. 5c) departs from cooling methods using air alone and proposes to use an array of pipes to provide shade. The pipes carry seawater that is thereby warmed and fed into the back evaporator, where it boosts water production. The pipes function in a similar manner to an unglazed solar collector and the estimate of their efficiency in transferring incident radiation into water is nominally 80% based on reference [7].

The CFD model described above was modified to cover these three options. For the purpose of comparison, a standard set of conditions was chosen corresponding to an ambient temperature of 30ºC, a relative humidity of 50% and solar radiation of 750 W/m^2. The baseline for the simulations was that developed for the UAE calibration case, modified to take into account the effects of plants in the greenhouse. First, the value of net solar radiation transmittance into the greenhouse was increased from 0.44 to 0.6 reflecting the decreased albedo of vegetation as opposed to bare soil (this value is consistent with that used in reference [8]). Secondly, the heat sinking due to evaporation was based on the crop reference evapotranspiration calculation [9] assuming an 80% coverage of the greenhouse floor. The input parameters for this calculation were averages for the whole planting area.

Initially, the possibility of solving the evapotranspiration equation coupled to the CFD model was contemplated. However, initial computations

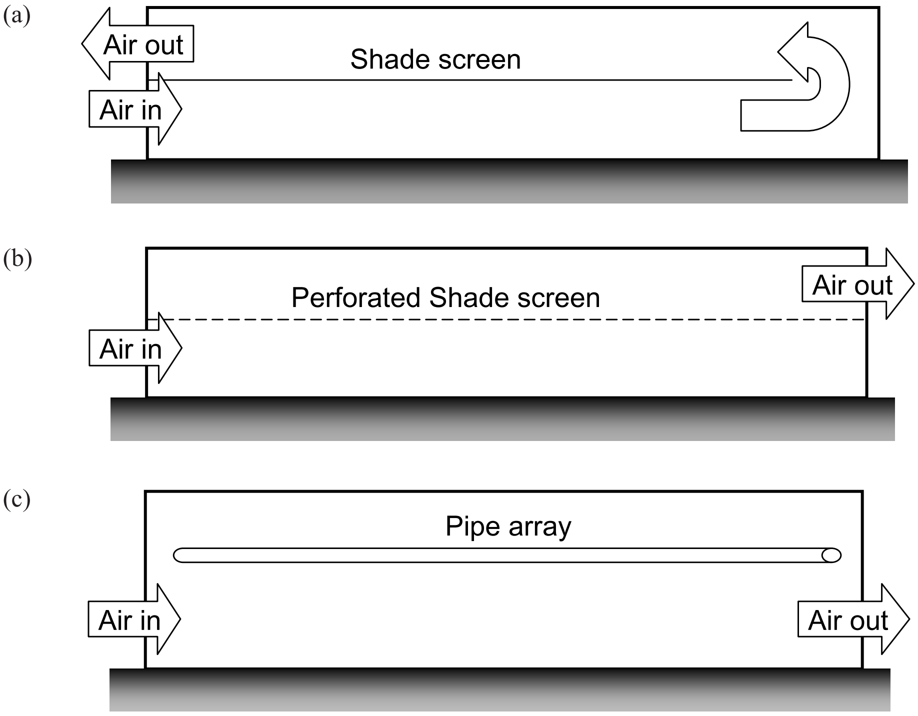

Fig. 5. Schematic cross sections illustrating the three design options considered. (a) C-shaped air path, (b) perforated shade screen and (c) shading by an array of pipes.

revealed that evapotranspiration varied little over the range of the study (see Fig. 9). We therefore based the evapotranspiration heat sink on the nominal value of 3 l/min for the whole greenhouse.

To estimate the rate of water production, some assumptions were made about the evaporation-condensation process downstream of the greenhouse outlet. We are only interested in comparing the three options for the design of the greenhouse, rather than evaluating any particular design of evaporator or condenser. Therefore the assumptions chosen were nominal but consistent, representing approximately the sizing of the condenser used in the UAE prototype. The rate of water production was assumed to be limited by the effectiveness of heat exchange in the condenser defined on the airside. The effectiveness was worked out on the basis of heat transfer coefficient for the whole condenser of 40 kW/ºC, by means of the standard method of calculation of number of transfer units (NTU) for a heat exchanger [10].

5. Results

The results of the modelling are summarised in Figs. 6, 7, 8 and 9 showing respectively air temperature, mean radiant temperature, water production and evapotranspiration. These variables are plotted against ventilation airflow. Separate curves are shown for the baseline design and the three proposed options. The temperatures are defined as averages for the planting area, calculated over a cuboid region extending from ground level to a height of 1.5 m.

A summarised comparison of the performance of the various options relative to the baseline, for a fixed ventilation airflow, is given in Table 3.

Table 3
Summary comparison for a ventilation airflow of 8.8 m^3/s. Figures are given as changes relative to the baseline case.

Option number	Description	Air temperature, ºC increase	Mean radiant temperature, ºC increase	Water production, % increase
1	Perforated screen	–0.3	–0.1	+5
2	C-shaped air path	+5	–3	+56
3	Pipe array	–1	–7.5	+63

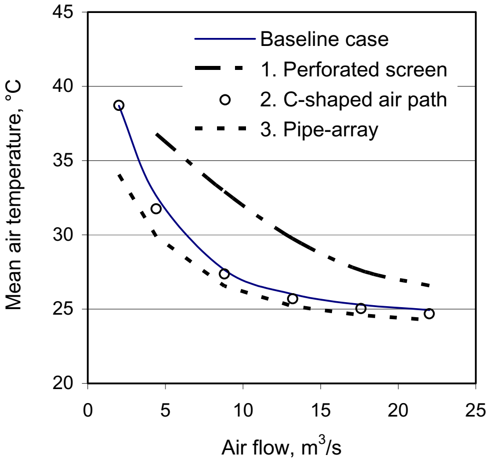

Fig. 6. Mean air temperature over the planting area of the greenhouse, comparing the three design options to the baseline case.

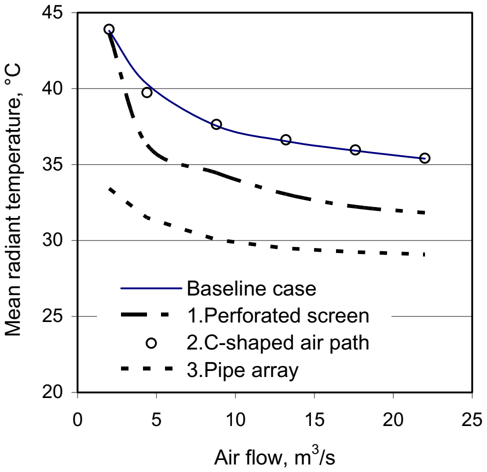

Fig. 7. Mean radiant temperature over the planting area of the greenhouse, comparing the three design options to the baseline case.

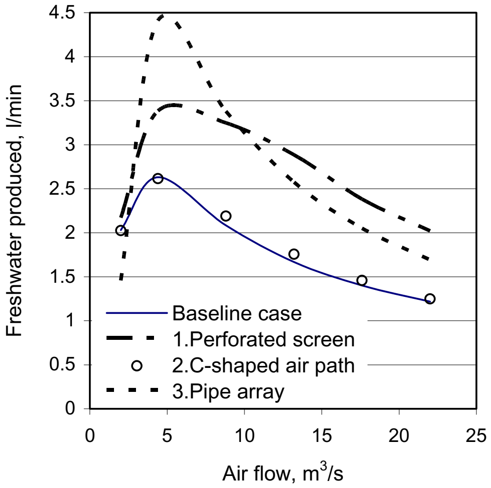

Fig. 8. Freshwater productions from the greenhouse for the various design options, comparing the three design options to the baseline case.

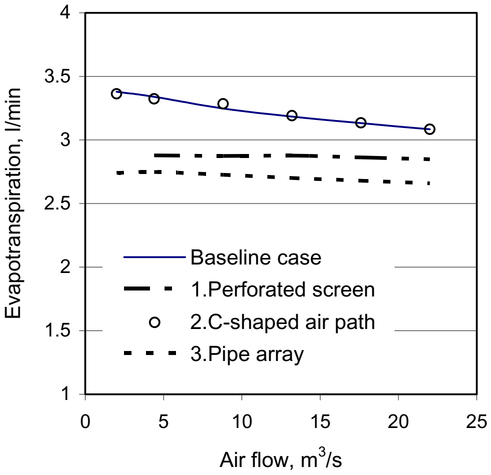

Fig. 9. Evapotranspiration rates from the plants inside the greenhouse, comparing the three design options to the baseline case.

6. Discussion and conclusions

In this study we have shown how the temperatures inside the Seawater Greenhouse are influenced by complex 3-dimensional patterns of air movement and by long-wave radiation from hot surfaces. This explains why simple network models do not represent adequately the behaviour observed.

The tendency for recirculation currents and mixing to occur can be understood by noting that cool air enters the greenhouse above the level of warmer air that is tending to rise from the hot floor of the greenhouse. In this situation the flow becomes unstable due to buoyancy effects. This is similar to the phenomenon of mixing ventilation, as distinct from displacement ventilation, as described in reference [11].

In an attempt to overcome this, the first design option uses a C-shaped air path to reduce recirculation and mixing and improve the heat extraction. Referring to Table 3, the analysis confirms that the air temperature in the planting area will decrease and water production will increase. However, the improvements are marginal. The practical construction of this type of greenhouse differs significantly from the existing designs. The condenser and evaporator are at the same end of the greenhouse. If they are kept as separate units then, as one is above the other, the height of each becomes restricted. Another approach may be to integrate the evaporator and condenser as one unit. Theoretically this could be advantageous as it removes the need to pump seawater from the front to the back of the greenhouse. The practical issues in implementing an integrated condenser-evaporator have yet to be fully explored.

The second option uses a perforated screen, dividing the greenhouse into lower and upper compartments with the upper compartment at a reduced pressure. The analysis confirms that improved cooling of the screen reduces the mean radiant temperature in the greenhouse. On the other hand, the air temperature in the planting area actually increases significantly. This is attributed to stagnation of the air towards the back of the planting area. At this point a large fraction of the airflow has already been diverted into the upper compartment. Therefore, although this method can improve water production, it does not give an overall benefit in cooling.

In this second option, we are wishing to obtain predominantly pressure-driven airflow through the screen in preference to buoyant effects. This requires a screen with an aperture of 5% or less and good sealing around the edge of the sheet to avoid parasitic airflows.

A variant of this option is to use screens with large apertures (e.g. 50%) allowing natural convection to enhance heat transfer. Although this case has not been analysed in detail, the performance is expected to lie somewhere between that of the baseline case and the perforated screen. Screens that provide shade by means of apertures have practical attractions compared to semi-opaque sheet plastic sheets. The optical properties of a semi-opaque sheet may change with time as it becomes dirty or the material degrades. Shade materials using apertures are less likely to deteriorate in this manner.

The third option, using an array of pipes to produce shade, is the only one giving a significant improvement by all the criteria applied. It is therefore the preferred option. The reason that it works the best is that the ability of water to extract heat from the greenhouse is superior to that of air alone, especially if the water is used to cool surfaces receiving sunlight directly.

Figs. 6–8 suggest that the optimal ventilation rate for cooling differs from that for water production. The optimum airflow for water production is of the order 5 m^3/s. For cooling, a flow of 10–20 m^3/s appears more appropriate. In reality this can be overcome partially by maintaining a large flow through the greenhouse while allowing some air to bypass the water production stages of the second evaporator and condenser. The drawback here is that some of the solar energy absorbed by the air in the greenhouse is effectively wasted as far as distillation is concerned. However, this drawback is less severe for the third option where pipes are used to provide shade. Here a substantial fraction of the solar energy is carried into the evaporator-condenser stage by the water rather than by the air. This tends to allow independent optimisation of flows for cooling and water production and is a further reason in favour of this option.

Finally, we note that this study confirms the feasibility of designing the greenhouse such that the amount of freshwater produced exceeds the evapotranspiration requirement.

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