

## A Comparison between Evaporation Ponds and Evaporation Surfaces as a Source of the Concentrated Salt Brine for Salt Gradient Maintenance at Tajoura's Solar Pond

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**الملخص:** واحدة من أكبر المشاكل التي تؤثر سلباً على تشغيل البرك الشمسية المتدرجة الملوحة وعلى استقرارها الحراري تتمثل في المحافظة على منحنى تدرج الأملاح داخل البركة. البركة التبخرية صممت لتوليد أو إنتاج الأملاح التي تفقد بواسطة انتشار الأملاح الصاعد من طبقة الحمل السفلى (طبقة التخزين) في البركة الشمسية. وهناك طريقة أخرى جذابة تتمثل في استخدام الأسطح التبخرية. في المناطق التي تهطل فيها الأمطار بمعدلات متوسطة وعالية يفضل استخدام الأسطح التبخرية على البرك التبخرية في توليد وإنتاج الأملاح. وفي المناطق التي تتميز بمناخ جاف عادة ما يفضل استخدام البرك التبخرية في إعادة تركيز المحلول الملحي.

تبحث هذه الدراسة في الفروق أو الاختلافات ما بين البرك التبخرية والأسطح التبخرية. حيث تم دراسة تأثير عمق البركة التبخرية على نسبة المساحة (النسبة بين مساحة البركة التبخرية إلى مساحة البركة الشمسية) وعلى التغيرات اليومية على تركيزات الأملاح للثلاث سنوات الأولى من التشغيل. أظهرت النتائج أن التبخير يمكن أن يكون طريقة معقولة لتوليد أو إنتاج المحلول الملحي. تخفيض أو تقليل عمق البركة التبخرية يحسن من قابليتها لإعادة تركيز المحلول الملحي. وكذلك يزيد من مساحتها السطحية لنفس كمية المياه المألحة المستخدمة. لذلك فإن الأسطح التبخرية تعتبر أكثر فعالية وأقوى من البرك التبخرية في إعادة تركيز الأملاح.

**Abstract:** One of the main problems that negatively affect the operation of salt gradient solar ponds and influence its thermal stability is the maintenance of salt gradient profile. Evaporation pond (EP) is designed to generate the salt which is lost by upward salt diffusion from the lower convective zone (LCZ) of the solar pond. Another attractive method is

the Evaporation Surface facility (ES). Regions with moderate to high precipitation favor Evaporation Surfaces over Evaporation Ponds. Dry climates will generally favor Evaporation Ponds for the brine re-concentration.

This paper investigates the differences between (EP) and (ES) both as a source for salt brine generation by evaporation. The effect of (EP) depth on the area ratio and daily variations of salt concentrations for three years of operation is shown. Results show that evaporation can be a reasonable method for salt brine generation. Reducing the depth of (EP) improves the capability of (EP) for brine re-concentration. It also increases the (EP) surface area for the same quantity of saline water used. Therefore, ESs are more powerful than Eps in salt re-concentration.

**Keywords:** Solar pond, Evaporation, Evaporation pond, Evaporation surface, Salinity profile, Area ratio, Concentration.

## 1. INTRODUCTION

A solar or salt gradient solar pond is usually artificial, although a few occur naturally where dissolved salts create a trap that can be tapped both for heat and to produce electricity. The water and bottom material of an ordinary pond, whether fresh or saline absorbs heat from the sun but loses it as the heated water expands and rises to the surface. The addition of salt makes water denser and heavier. If the salt is added at the pond bottom, a salt gradient is created between the surface and the deeper waters. A typical artificial solar pond has three gradients or salinity zones. The surface zone, upper convective zone, (UCZ) up to 0.5 m deep, has the lowest salinity. In the middle zone, non convective zone, (NCZ), 1~1.5 m deep, salt content increases with depth. The storage zone, lower convective zone, (LCZ) at the bottom, which may be several meters deep has the highest salinity and therefore the densest, heaviest water.

It is in this bottom layer that trapped heat is stored. A solar pond is an effective solar energy collection storage device which presents a relatively simple and economic method of providing low grade energy with the advantage of annual storage cycle.

A (SGSP) located in Tajoura to the east of Tripoli has been designed and constructed by the Center for Solar Energy Studies, (CSERS), in joint cooperation with a Swiss company as an experimental facility. Tajoura's Experimental Solar Pond (TESP) consists of a main SGSP with a surface area of 830 m<sup>2</sup> and a total depth of 2.5 m and an evaporation pond (EP) with a surface area of 105 m<sup>2</sup> and 1.5 m depth. The salt concentration profile is constructed with three zones, the (UCZ) of 0.30 m thickness and a salt concentration of about 41 kg/m<sup>3</sup>, the (LCZ) of 1 m thickness and salt concentration of 256.94 kg/m<sup>3</sup>. Separating these two zones is the (NCZ) of 1.2 m thickness and variable salt concentration.

The pond, fully equipped with systems to monitor all relevant parameters, is designed as an experimental facility enabling the investigation of various aspects of pond performance.

There are many factors that affect the pond stability and its performance during daily operation of the SGSP and in some locations limit their use, were recognized and several schemes for solution have been proposed to eliminate or minimize their effect. These problems include, among others, salt diffusion, wind mixing, evaporation, dust and dirt falling on pond surface. Based on the working principle of a SGSP, it is necessary to build the salinity profile in such a way that allows the high concentration brine at the bottom layer and low concentration brine at the upper layer of the pond. Between these two layers, a salinity gradient profile has to build. Naturally, salt diffuses from high salt concentration layer to the low salt concentration layer, diffusivity of the salt is affected by pond temperature and the salinity profile.

In previous studies [1-3], the authors have shown that the (EP) of Tajoura's Experimental Solar Pond (TESP) is under sized and can provide only about 30% of the salt required by a Salt Gradient Solar pond (SGSP). The anticipated size of (EP) was estimated and presented in those studies under different design conditions, including Summer, Autumn and Spring designs, while the winter design was excluded due to the low rates of net evaporation during the winter season.

In addition, the results presented were predicted for the first three years of operation. The daily variations of brine concentration in the (EP) of (TESP) and those based on different designs were predicted and discussed under different scenarios. The quantities of brine provided by the evaporation pond and that required by SGSP were predicted for both cases of surface water flushing (fresh water and seawater) under the different design conditions as shown in Table (1).

The annual rate of this natural diffusion of salts from high to low concentration was estimated by Tabor [4] to be in the range of 20-30 (kg/m<sup>2</sup>-yr) depending on the thickness of NCZ, the temperature profile and the concentration difference between the UCZ and the LCZ. A major concern related to the use of solar ponds is salt gradient maintenance. Over time, salt diffuses from the LCZ to the UCZ. To maintain the salinity gradient surface brine has to be removed and replaced with fresh water (or seawater) consequently, more salt has to be added to the LCZ. One way of recycling the salt is to re-concentrate the removed surface brine in an evaporation pond.

Operating SGSP starts with building the required salt gradient profile and filling the EP with sea water. During the heating up period, the storage zone temperature increases gradually which increases the salt diffusion rate and thus leading to the problem of thermal stability and keeping the salt gradient profile within a certain margin.

Providing big quantities of salt that are

required for salinity gradient maintenance of SGSP is a costly issue in terms of first cost and transportation costs. For this reason, many methods were proposed for re-concentration by using evaporation. These methods are; Evaporation Pond, Evaporation surface, Enhanced Evaporation Net System.

The evaporation pond, EP, is designed to generate the salt which is lost by upward salt diffusion from the LCZ of the solar pond. It consists of the land, lining, sea-water or low concentration brine. The driving force for brine re-concentration is evaporation. Dry climates generally favor evaporation ponds for brine re-concentration.

Another significant method is a brine re-concentration by using Evaporation Surface, ES. The purpose of the facility is to recycle salt from the upper convective zone UCZ for reuse in the lower convective zone LCZ of the solar pond. University of Illions solar pond uses this facility [5]. The brine re-concentration system is the south berm of the solar pond and has an approximate surface area of 1000 m<sup>2</sup> and a 10o southward slope. The berm, which is, used both as an unloading surface for initial salt charging of the solar pond and for brine re-concentration, is lined with 1 mm thick high density polyethylene. A submersible pump in the pond extracts UCZ brine for re-concentration. The brine drains to the southwest corner of the berm into a buried plastic septic tank. A second submersible pump in the drainage tank re-circulates the brine on the berm surface until the

brine concentration has reached a specific level. The brine is sprayed over the berm surface by rotating lawn- type sprinklers. The concentrated brine (usually set at 23% weight concentration) is then re-injected into LCZ of the solar pond. The system shuts down whenever the relative humidity indicates low potential for evaporation. Upon system shutdown, the re-circulating brine drains into the septic tank once the tank is filled. This is the primary mechanism that allows the system to operate in climates with moderate to high precipitation. The system consists of a surface that has a thin film of brine pumped over its surface when the weather is favorable for evaporation. Shutdown occurs during high humidity periods and the system has the ability to shed any precipitation that may fall. Regions with moderate to high precipitation favor Evaporation Surfaces over Evaporation Ponds. Dry climates will generally favor Evaporation Ponds for the brine re-concentration.

The brine re-concentration system has been incorporated into the design of the University of Illions half- acre salt gradient solar pond facility. An important feature of the system is its ability to keep precipitation from diluting the brine. The basic elements of the brine re-concentration system are the shallow sloping lined surface (approximately 1100 m<sup>2</sup>), drainage tank, circulation pump, water distribution system, extraction pump, and automatic control system.

At the El-Paso Solar Pond [6], the original evaporation pond area of 800 m<sup>2</sup>

was undersized. In an attempt to increase evaporation without building a new evaporation pond, an enhanced evaporation net system was designed and installed in 1988. The system consisted of two 50 m<sup>2</sup> woven fabric nets with approximately 40 percent air space between the cloth strands. Brine was pumped through the irrigation type drip tube at the top of the nets and allowed to run over the nets for evaporation.

The objective of this paper is to investigate the differences between (EP) and (ES) both as a source for salt brine generation by evaporation.

## 2. MATHEMATICAL MODELING

A theoretical model was developed to calculate the needed evaporation pond area, with the assumption that volume flow rates and other parameters are taken as average values over a particular period, annual averages were preferred and the system was assumed to undergo a steady state, steady flow process. Numerical analysis approaches with computer algorithms were incorporated to predict the required results.

### 2.1 Mass and Volume Balance

Figure (1) shows the schematic of flows in a Closed Cycle Salt Gradient Solar Pond (CCSGSP) where:

- $Q_1$  = Makeup water (m<sup>3</sup>/ period).
- $Q_2$  = Evaporation from SP (m<sup>3</sup>/ period)
- $Q_3$  = Rainfall to the SP (m<sup>3</sup>/ period)
- $Q_4$  = Overflow to the EP (m<sup>3</sup>/ period)
- $Q_5$  = Evaporation from EP (m<sup>3</sup>/ period)
- $Q_6$  = Rainfall to the EP (m<sup>3</sup>/ period)
- $Q_7$  = Saturated brine injection from the EP

to SP (m<sup>3</sup> / period)

$Q_s$  = Heat input to SGSP and EP by solar radiation (W/m<sup>2</sup>).

$m_s$  = Solid salt accumulation in the EP (kg salt / m<sup>3</sup> of brine)

$C_1$  ,  $C_4$  and  $C_7$  are the corresponding salt concentrations (kg salt /m<sup>3</sup> of brine)

$A_{sp}$  and  $A_{ep}$  are SP and EP areas respectively (m<sup>2</sup>)

ST = Total salt transport from the SP bottom to the surface (kg/m<sup>2</sup>. priod)

A theoretical basis for the design of a CCSGSP system has been presented by Alagao et al (1994), [8]. A prototype pond system was constructed to establish the operating characteristics of CCSGSPs and to validate a theoretical model for them. In order to maintain salt balance in the SP,

$$C_7 Q_7 = A_{sp} ST \dots \dots \dots (1)$$

the amount of brine injected must equal the

$$Q_4 = Q_1 + (Q_3 - Q_2) + Q_7 \dots \dots \dots (2)$$

total salt transport to the surface. that is;

$$(Q_3 - Q_2) = A_{sp}(R - E_{sp}) \dots \dots \dots (3)$$

Volume Balance at the SP yields;

we also know that;

where: R and Esp are Rainfall and

$$Q_4 = Q_1 + A_{sp}(R - E_{sp}) + \frac{A_{sp}(ST)}{C_7} \dots \dots (4)$$

Evaporation at the SP in (m/period).

$$Q_1 C_1 + Q_7 C_7 = Q_4 C_4 \dots \dots \dots (5)$$

Combining relations (1), (2) and (3) gives;

Salt Balance at the Solar Pond gives;



$$Q_1 = A_{sp} \left[ (ST) \left( \frac{1}{C_4} - \frac{1}{C_7} \right) + (E_{sp} - R) \right] \left[ \frac{C_4}{C_4 - C_1} \right] \dots \dots \dots (6)$$

Equation (6) gives the volume of makeup water needed for a known SP size .

Any salt input into the system associated with  $Q_1$  is allowed to accumulate in the EP and is equal to  $(Q_1 C_1)$ ;

$$ms = Q_1 C_1 \dots \dots \dots (7)$$

Volume balance at the EP results in;

$$Q_4 = (Q_6 - Q_5) + Q_7 \dots \dots \dots (8)$$

which can be written as;

$$Q_4 = A_{ep}(E_{ep} - R) + Q_7 \dots \dots \dots (9)$$

Where,  $E_{ep}$  is the amount of evaporation in (m / period) at the EP surface , Equation (9) is used to calculate the EP area as;

$$A_{ep} = \frac{(Q_4 - Q_7)}{(E_{ep} - R)} \dots \dots \dots (10)$$

Combining equations (1) , (4), (6) and (10) yields;

$$A_{ep}(E_{ep} - R) = A_{sp} \left\{ (ST) \left( \frac{1}{C_4} - \frac{1}{C_7} \right) \left[ \frac{C_4}{C_4 - C_1} \right] + (E_{sp} - R) \left[ \frac{C_1}{C_4 - C_1} \right] \right\} \dots \dots \dots (11)$$

For fresh water make up ( $C_1=0$ ) , equation (11) becomes;

$$A_{ep}(E_{ep} - R) = A_{sp} \left\{ (ST) \left( \frac{1}{C_4} - \frac{1}{C_7} \right) \right\} \dots \dots \dots (12)$$

## 2.2 Energy Balance

In initial operation of solar ponds, the usual practice is to build the salt gradient profile first, then filling the evaporation pond with sea water. During startup period the temperature of storage zone gradually increases which affects the rate of salt

diffusion from the lower convective zone to the upper convective zone, leads to the problem of thermal stability and keeping the salt gradient profile within a certain margin for the main pond.

In order to operate the pond effectively, it is important to know the time required for re-concentration of brine in the evaporation pond from sea water salt concentration of about (3.5%) to the desired brine concentration of about (35%) which is injected to the storage zone to maintain the stability of salt gradient profile of the solar pond.

For the purpose of analysis, a brine re-concentration simulation model was employed at the University of Illions SGSP to simulate the evaporation process at the evaporation surface ES [5]. The model consisted of a lumped capacitance assumption for a shallow evaporation

pond that has energy exchanges due to solar radiation, sky radiation, convection

to atmosphere, conduction to ground and evaporation. Ground conduction was ignored. In this study, The terms representing the sky radiation and the evaporation energy were modified so that the model used in this paper can be written as;

$$m c \frac{dT}{dt} = \alpha_s A_{ep} Q_s - h_r A_{ep} (T - T_{sky}) - h_c A_{ep} (T - T_a) - E_{fw} A_{ep} \alpha_{ep} L \rho_w \dots \dots \dots (13)$$

Where;

m: mass of brine to be evaporated (kg), c: specific heat (J/kg.K), T: temperature (K), t: time (period),  $\alpha_s$ : radiation absorptivity coefficient,  $h_r$ : radiative heat transfer coefficient (W/m<sup>2</sup>.K),  $T_{sky}$ : sky temperature (K),  $h_c$ : convective heat transfer coefficient

- The fourth term accounts for the heat loss from evaporation pond surface due to convection,  $Q_{s,c}$  in (W/m<sup>2</sup>) and;
- The fifth term is the heat loss from evaporation pond due to evaporation,  $Q_{s,e}$  in (W/m<sup>2</sup>).

The value of evaporation surface solar

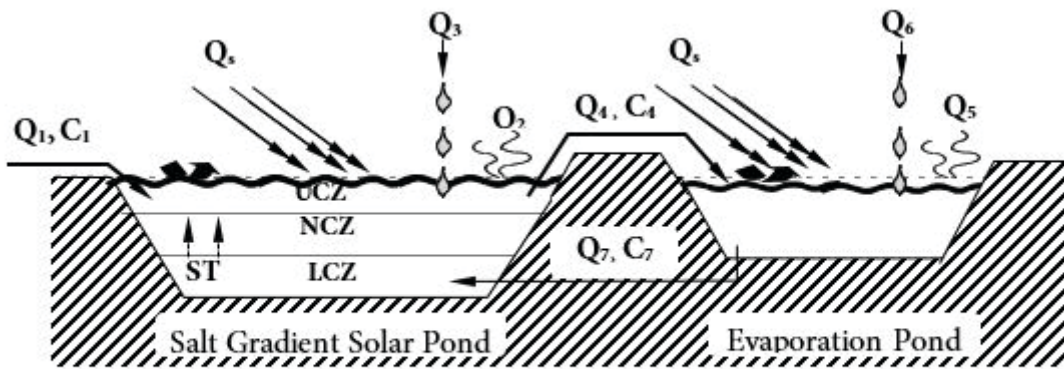


Figure (1): Schematic diagram of SGSP / EP system showing the various mass and volume balance components.

(W/m<sup>2</sup>.K),  $T_a$ : ambient air temperature (K),  $E_{fw}$ : evaporation rate from fresh water (m/period),  $\alpha_{ep}$ : the reduction of evaporation due to salinity from EP, L: latent heat of vaporization (kJ/kg) and  $\rho_w$ : density of the water (kg/m<sup>3</sup>).

Referring to Figure (2), the various terms in equation (13) are as the following;

- The first term is the heat stored in the evaporation pond brine,  $Q_{s,s}$  in (W/m<sup>2</sup>).
- The second term accounts for the heat input to the evaporation pond by solar radiation,  $Q_s$  in (W/m<sup>2</sup>).
- The third term is the heat loss from evaporation pond surface due to radiation,  $Q_{s,r}$  in (W/m<sup>2</sup>).

absorptance,  $\alpha_s$  is taken to be equal to 0.9 from reference [5].

The coefficient of convective heat transfer ( $h_c$ ) in (W/m<sup>2</sup>. K) is based on correlation from Kishore and Joshi (1984) [7];

$$h_c = 5.6779 (1 + 0.671 \times V) \dots \dots \dots (14)$$

The radiation heat transfer coefficient ( $h_r$ ) was assumed to be equal to 5.7 (W/m<sup>2</sup>.K) for shallow solar ponds [7].

The model is applied to the evaporation pond of TESP, with surface area of 105 (m<sup>2</sup>). For the method of solution and implementation procedure of the model, see references [1-3].

### 3. RESULTS AND DISCUSSION

Due to the intermittent nature of solar energy, solar energy systems will have to be sized according to a pre-specified time. For this purpose, Table (1) shows the required area ratios under the prevailing conditions in Tripoli for different design conditions and both types of surface water flushing. The winter design was excluded due to

its low rates of net evaporation from the evaporation pond. It should be noted that the design conditions considered in this study were defined as follows;

- Spring Design Condition: The prevailing weather conditions (ambient temperature, relative humidity, wind speed...etc) in Tripoli-Libya during the month of March were used in this case.

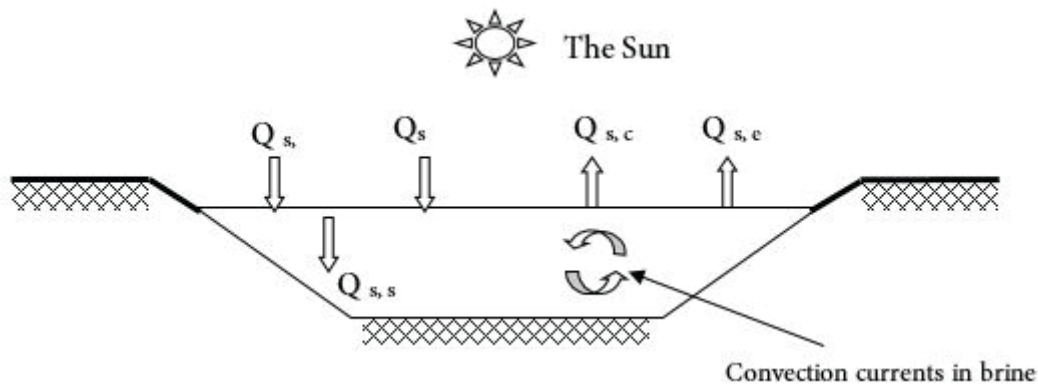


Figure (2). The components of energy balance model applied to Evaporation Pond.

- Summer Design Condition: The prevailing weather conditions (ambient temperature, relative humidity, wind speed...etc) in Tripoli-Libya during the month of June were used in this case.
- Autumn Design Condition: The prevailing weather conditions (ambient temperature, relative humidity, wind speed...etc) in Tripoli-Libya during the month of September were used in this case.
- Winter Design Condition: The design condition was not considered.

#### 3.1 The Salt Concentration Profile Maintenance:

The quantities of brine required by the SGSP of TESP (830 m<sup>2</sup>) and that provided by

the EP based on different design conditions were predicted for both cases of surface water flushing (fresh water and seawater) for three years of operation. It should be noted that these predictions simulate the real case scenario by assuming the following conditions;

- The EP and the SGSP are completely coupled together through  $Q_4$  (over-flow from SGSP) and  $Q_7$  (high concentrated brine injection).
- The 1st of January was assumed as the starting operating day.
- The natural rate of salt diffusion was assumed as 16.6 kg/m<sup>2</sup>-year (as assumed by TESP team).
- The LCZ concentration is allowed to



decrease from 26% to 22%. These were taken as the upper and lower limits of marginal stability.

The overall year contribution of EP under different design conditions in providing the required salt quantities for both types of surface water flushing is shown in Table (1). These results show the differences existing between the design conditions considered for the first three years of operation. The highest contribution comes from spring design for

both types of surface water flushing. Also, for each design condition, the contribution increases by year.

None of the design conditions can provide a complete quantity of the salt required for the three years. This is, of course, due to the reduction in the concentration levels resulting from the precipitation rate during the winter season, and can be overcome by storing salt from the summer season for use during the winter season.

**Table (1): Comparison between the quantities of salt provided by (EP) under three years of operation for different design conditions.**

| Design | Area Ratio<br>( $A_r = A_{ep} / A_{sp}$ ) |           | Percentage of salt provided by EP for fresh water flushing, % |                    |                    | Percentage of salt provided by EP for sea water flushing, % |                    |                    | Overall (%) |           |
|--------|---|-----------|---|--------------------|--------------------|---|--------------------|--------------------|-------------|-----------|
|        | Fresh water                               | Sea water | 1 <sup>st</sup> yr  | 2 <sup>nd</sup> yr | 3 <sup>rd</sup> yr | 1 <sup>st</sup> yr  | 2 <sup>nd</sup> yr | 3 <sup>rd</sup> yr | Fresh water | Sea water |
| Spring | 0.65                                      | 28.40     | 44  | 89                 | 87                 | 39  | 92                 | 95                 | 74          | 76        |
| Autumn | 0.32                                      | 20.20     | 30  | 73                 | 79                 | 32  | 85                 | 93                 | 61          | 71        |
| Summer | 0.17                                      | 14.40     | 21  | 36                 | 48                 | 26  | 69                 | 88                 | 36          | 62        |
| TESP   | 0.13<br>(constructed)                     |           | 20  | 33                 | 44                 | 19  | 33                 | 44                 | 33          | 32        |

Table 1. summarizes the predicted quantities of salt that can be contributed by (EP) (as, a percentage). It can be seen that (EP) provide 20% to 40% during the first year and 45% to 95% during the third year depending on the design selected. Comparing the percentage of salt provided for different designs, it can be clearly seen that the Autumn design presents a favorable condition. It provides a reasonable percentage reaching 79% in the case of fresh water surface flushing and 93% in the case of seawater surface flushing with

a relatively low area ratio. It should be noted that; the last column in the table represents the overall average percentage for the quantity of salt provided by EP for both types of surface water flushing under different design conditions for the first three years of operation.

### 3.2 Comparison between Evaporation Ponds and Evaporation Surfaces:

This section investigates the effect of EP depth on the area ratio and the related performance of EP. In order for the EP

to provide the required amount of salt, decreasing the EP depth leads to increasing the EP area. The idea of using large surface areas is very attractive, especially in areas of low to moderate net evaporation rates.

Figures (2) and (3) show the effect of decreasing the EP depth on the area ratio for both cases of surface water flushing and under different design conditions. Noting that a depth of 0.2 m was treated in this study as an evaporation surface (ES) condition.

Figures (4) and (5) show the daily variations in salt concentration for various EP depths under the Autumn design condition. It can be seen that the improvement in salt concentration increases for the ES, especially

during the first year where the concentration has reached 35% at the start of the summer months.

The rate of evaporation will be increased by bigger surface area. The greater the exposed surface, the faster the evaporation. This is because water molecules need to be at the water surface to evaporate. With a big surface area more water molecules can be at the water surface and therefore more water can evaporate. In general the overall rate of evaporation will depend on the surface area exposed to the drying effects of the environmental conditions: Temperature, humidity, presence or absence of adjacent air and its movement.

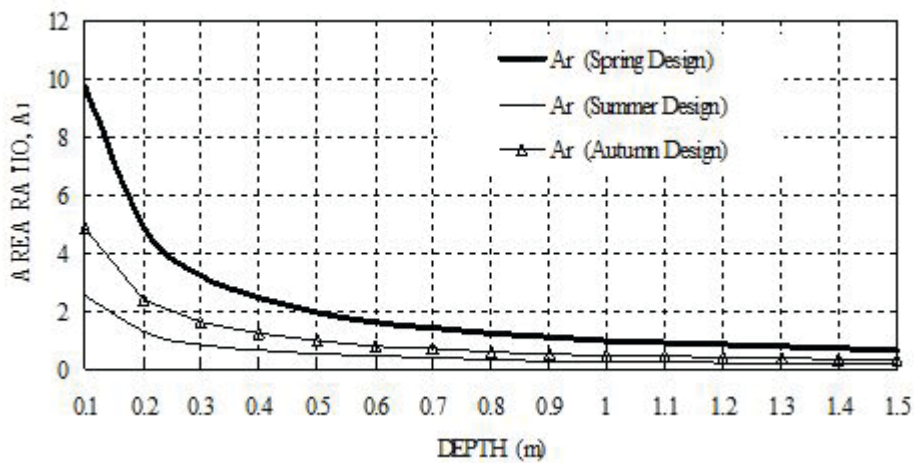


Figure (3). Variation of area ratio with depth for different design conditions for fresh water surface flushing.

#### 4. CONCLUSION

The main outcome of this study can be summarized as follows;

- Reducing the depth of EP improves the capability of EP for brine re-concentration. It also increases the surface area of EP for the same quantity of saline water used.
- Evaporation surfaces are more effective facility than Evaporation Ponds in salt re-concentration.
- Evaporation Surfaces are preferred for areas with moderate to high precipitation over Evaporation Ponds. Whereas, in hot and dry climates Evaporation Ponds are suitable for brine re-concentration.

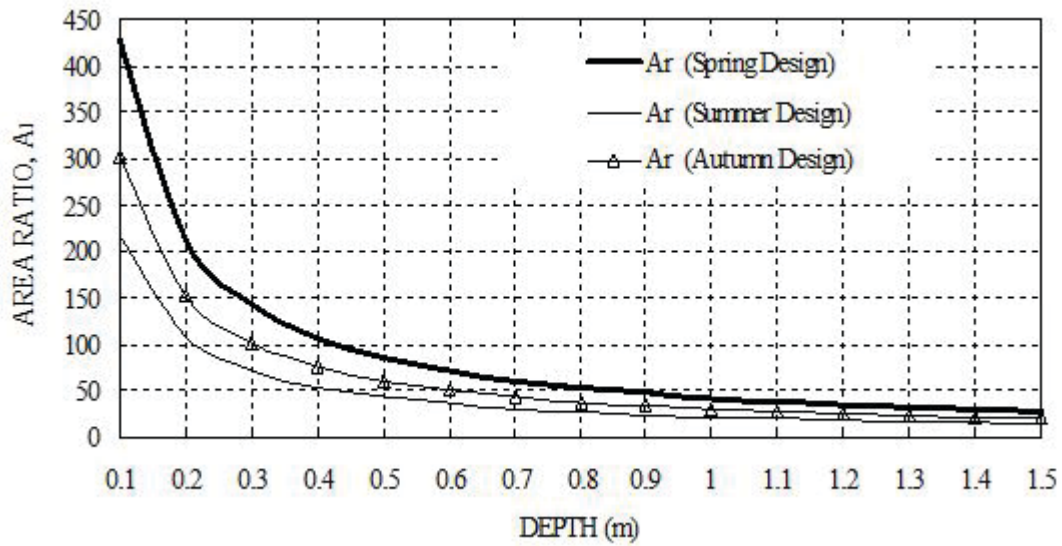


Figure (4). Variation of area ratio with depth for different design conditions for seawater surface flushing.

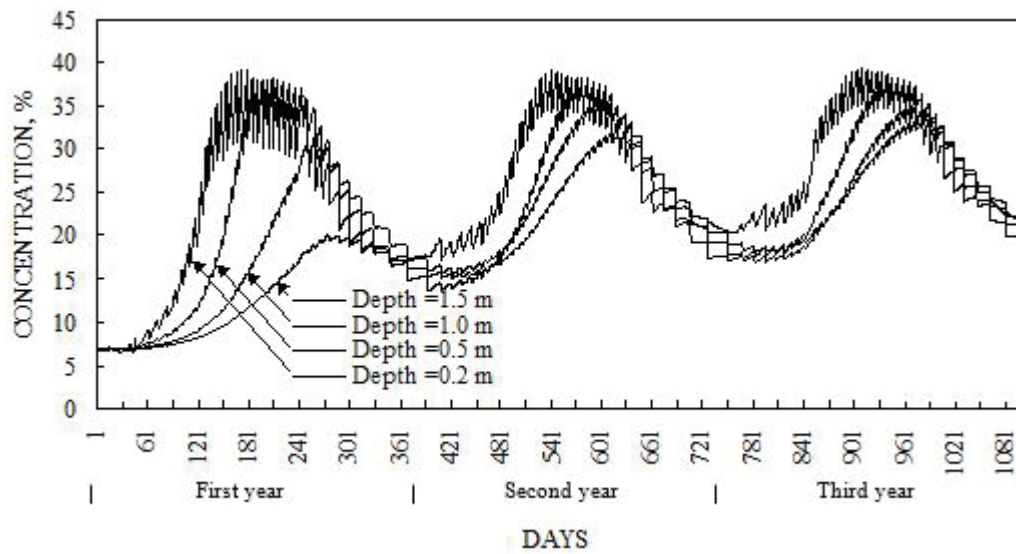


Figure (5). Daily variation of salt concentrations with depth in EP started at JAN with primary salt concentration (7%), brine reject from RO-Plant for fresh water surface flushing under Autumn design for three years of operation.

- The flushing water concentration significantly affects the area ratio and the quantity of water used for surface flushing.
- Although the model used was developed to be used under the closed loop condition, yet, part of the overflow was rejected due to the high quantities of flushing by sea water.
- EP can provide 20% to 40% of the salt required by SGSP during the first year of operation and 45% to 95% during the third year of operation depending on the design selected.

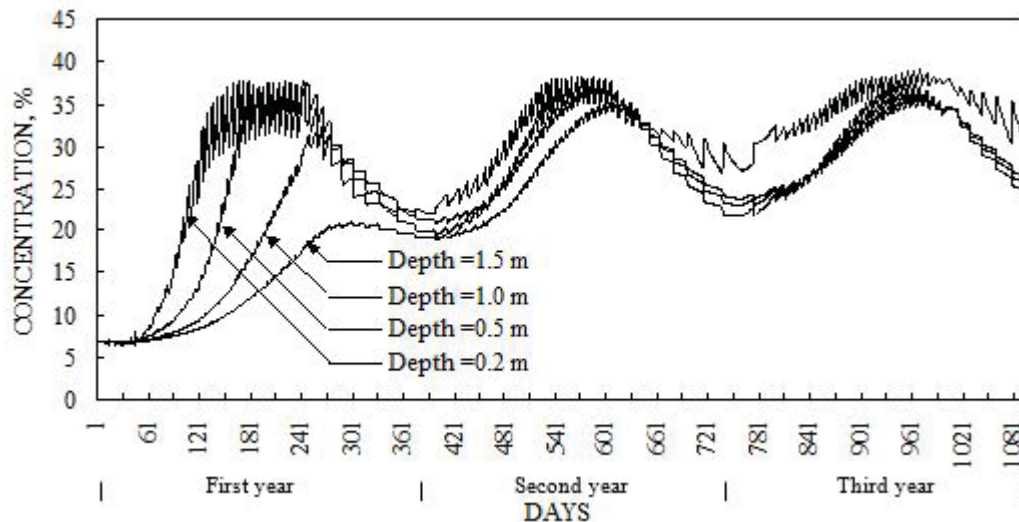


Figure (6). Daily variation of salt concentrations with depth in EP started at JAN with primary salt concentration (7%), brine reject from RO-Plant for seawater surface flushing under Autumn design for three years of operation.

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