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DESIGN AND PERFORMANCE ASSESSMENT OF INTEGRATED MEMBRANE DESALINATION/SOLAR POND SALT RECOVERY SYSTEM

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ABSTRACT

Brine disposal is one of the main issues addressed lately when speaking about applying desalination process. This paper presents a statistical technique to estimate evaporation pond recovery factor according to metrological parameters. A multivariate regression model is adopted to predict the effect of the different conditions on the pond recovery ratio. It is a general technique and can be adopted for different types of design. A linear multiple regression model with coefficient of determination (R2) of 0.91 has been developed whereby five investigated parameters have been related to formulate the model. The used model has been applied for a brine disposal scheme comprising nanofiltration and reverse osmosis system for producing water and solar pond for integrated salt recovery.

Keywords: desalination, nanofiltration, multivariate regression, sea water, evaporation pond.

INTRODUCTION

Freshwater scarcity is a major problem worldwide; desalination takes place as a solution to overcome this problem (Akili D. K. *et al*., 2008).Desalination has been used to increase water resources for some small communities and also for large cities (Qingrong Z. and Xiuli L., 2016), as well as providing fresh water to the industrial sector (BennettA., 2001; Ali A. and Adel O., 2011).Due to technological progress, desalination technology has become a feasible, and a cost-effectively option for producing water with the required quality. Nowadays, installation of large scale desalination plants is a great challenge; due to environmental and ecological concerns regarding brine disposal options (Mickley M. 2012, Manh H. *et al*., 2015).

Feed water pre-treatment is one of the major important factors in determining the successful operation of the desalination process. Conventional pre-treatment includes "but not limited to" mechanical treatment (cartridge filters, media filters) chemical treatment e.g. flocculation, coagulation, pH adjustment, acid treatment, anti-scalent addition (Van der B. B. and Vandecasteele C. 2002; SikoraJ., Hansson C. and EricssonB. 1989; Brehant A. *et al*., 2002). Main drawbacks of the conventional pre-treatment are the complexity of the process and large footprint (Van HoopS. *et al*., 2001).

A new trend in desalination pre-treatment include pressure-driven membrane processes (Microfiltration (MF), Ultrafiltration (UF) and Nanofiltration (NF)). The application of NF in seawater desalination has gained significant attention due to its selective removal of divalent ions which reduces the need of anti-scalant doses as well as increasing membrane lifetime (Takeshi M. 2001).

The pore size of NF membranes has been estimated to be in the range of 0.4-0.8nm (Abdel Nasser A. M. and Hassan El-banna S. F. 2013). The main advantage of using NF membranes process is its ability to separate divalent ions with high rejection values especially Ca and Mg (HilalN. *et al*., 2004). While, there are many factors affect the performance of NF membranes such as feed flow rate, feed pressure and feed concentration. Variation of operating parameters affect the performance of NF process in terms of water quality, power consumption and the recovery rate (Yuefei S., *et al*., 2012; Ali A., Adel O. S., Malak H. *et al*., 2015).

The main environmental concern for using desalination process is the brine disposal issue. There are different disposal options for brine including: deep well injection, land disposal, surface water discharge, Sal-proc process, mechanical/thermal evaporation and evaporation ponds (Muftah H. E. *et al*., 2011). The use of solar evaporation ponds for desalination brine is suitable to dispose reject brine from inland desalination plants in arid and semi-arid areas due to the abundance of solar energy (Mushtaque A *et al*., 2000). The use of solar evaporation ponds for desalination brine is an added value to the desalination process economics; not only from the environmental point of view but due to the revenues gained from precipitated salts (Mohamed H. S. *et al*., 2015; Ghada A., *et al*., 2014; Mohamed H. S. *et al*., 2015)

In this study, a multivariate regression model is formulated to predict the recovery of solar evaporation pond dependent on metrological conditions as well as feed water salinity. A proposed desalting scheme comprising nanofiltration, reverse osmosis and integrated solar evaporation ponds as an option for desalination/brine management scheme based on the developed model.

METHODOLOGY

a. Desalination/ Solar evaporation pond scheme

A scheme comprising NF/RO/pond system is proposed as an integrated process for desalination/brine disposal management system. Figure-1 shows the developed integrated membrane system in addition to solar evaporator/crystallizer ponds with seawater feed water capacity 1000 m^3/d.

ARPN Journal of Engineering and Applied Sciences

Feed seawater is subjected to NF unit (recovery 55%) (Mohammad A.K., *et al.*, 2000; Ghada A. *et al.*, 2012) and the concentrate stream will be directed to solar evaporation pond 1, then a concentrated stream from pond 1 is subjected to pond 2 where Mg is precipitated. The permeate stream of NF is directed to RO system with estimated recovery 50%, the produced reject stream is directed to halite precipitation pond. Nanofiltration process rejections have been estimated using a previously developed model by the author [24]. Table-1 shows the estimated operating conditions for NF membrane system as well as the estimated ion rejection.

b. Multivariate regression model

Multiple regression method is used to predict recovery factor of a solar evaporation pond. The correlation developed are based on published data of solar evaporation ponds (León-Hidalgo M.C., 2011; Agha K. R. *et al*., 2001; Assad H. S *et al*., 2016; Dae H. K., *et al*., 2007; Paul J.T. and Wilfried G.J. 2008; Agha K.R. 2009; Sura T. *et al*., 2010; CarusoG. *et al*., 2001VelmuruganV. and Srithar K. 2007). Published data have been collected, screened and compiled to formulate the regression model. Five parameters were selected and investigated as the independent variables of the multivariate analysis, and one dependent variable which is the pond recovery. These variables are feed TDS value, pond area, wind speed, average temperature, and pond depth.

Correlation matrix investigates the relationship between the selected variables. It was found that there is a strong relationship between the investigated variables and the predicted pond recovery. Table-2 shows selected compiled data used for model formulation.

Table-1. NF operating and rejection of main ions (Ghada A., *et al*., 2012).

Pressure 22 bar, Recovery; 55%			
Ion	**Feed ion conc.** (mg/l)	**Permeate ion conc.** (mg/l)	**Reject ion conc.** (mg/l)
Cl	22780	12248	35652
Na	12860	7332	19616
Ca	481	95	952
Mg	1608	191	3339.8
TDS	38000	23431	55806

Table-2. Selected compiled data used for model formulation.

Feed water salinity "TDS" mg·L^{-1}	**Pond Recovery** %	**Wind Speed m/s**	**Temp.** (avg.) "°C"	**Pond Depth "m"**	**Pond Area "m^2"**	**Ref.**
291740	8.8	1.6	20	2	0.24	León-Hidalgo M.C. *et al*., 2011
2000	20	8.6	70	1.5	104	Agha K. R. *et al*., 2001
2600	19.7	3.7	60	0.9	8	Assad H. S *et al*., 2016
2400	33	7.7	23.5	2	1.25	Dae H. K., *et al*., 2007
3000	12	6.5	40	10	25000	Paul J.T. and Wilfried G.J. 2008
4900	14	0.56	70	2.5	75.9	AghaK.R. 2009
5250	43	5	40	1.5	7	Sura T. *et al*., 2010
7000	50	3.61	55	3.5	625	CarusoG. *et al*., 2001
12000	57.8	3.9	40	0.3	0.63	VelmuruganV. and SritharK. 2007

ARPN Journal of Engineering and Applied Sciences

Table-3. Coefficient of determination (R2) and the error probability (P-value).

Summary output

Regression Statistics	
Multiple R	0.954459
R Square	0.910991
Adjusted R Square	0.762643
Standard Error	8.73414
Observations	9

ANOVA

	df	**SS**	**MS**	**F**	**Significance F**
Regression	5	2342.304	468.4609	6.140914	0.083056
Residual	3	228.8556	76.2852		
Total	8	2571.16			

	Coefficients	**Standard Error**	**t Stat**	**P-value**	**Lower 95%**	**Upper 95%**
Intercept	2.391971	12.78596	0.187078	0.863536	-38.2987	43.08261
Feed salinity	0.004493	0.001068	4.208016	0.024508	0.001095	0.007891
Wind speed	3.024609	1.254821	2.410391	0.094984	-0.96879	7.018009
Temperature	-0.17139	0.180044	-0.95191	0.411369	-0.74437	0.401596
pond area	0.025423	0.018361	1.384609	0.260183	-0.03301	0.083858
pond depth	-0.65226	0.458989	-1.42109	0.250404	-2.11297	0.808445

RESULTS AND DISCUSSIONS

First, the correlation matrix has been investigated the relationship between the selected variables. It was found that there is a strong relationship between the investigated variables and the pond recovery. Table 3, shows the coefficient of determination (R^2) and the error probability (P-value). The equation is valid for low salinities as well as small and experimental ponds, for large capacities and salinities the equation will be multiplied by β where β equals 0.1, salinity limit for the equation is TDS 180,000 mg/l.

The formulated model can be written as:

$$\text{Pond recovery} = (2.391971+0.004493 (S) + 0.025423 (A) + 3.024609 (Ws) -0.17139 (T)-0.65226 (H) \quad (1)$$

Where
S = feed water salinity to pond (mg/l)
A = pond area (m^2)
Ws = wind speed (m/s)
T = temperature ◦c
H = pond depth (m)

The area of evaporation pond is a function of volumetric flow rate and evaporation rate (ShayyW.H *et al.*, 2000)

$$A = (Q/E)*S \quad (2)$$

Q: m^3/d

Where
S = salinity factor

The use of nanofiltration in the proposed scheme as a pretreatment for reverse osmosis desalination process is to avoid magnesium sulfate to co-precipitate with NaCl in the evaporation pond. By applying the formulated model for the proposed scheme NF reject brine, the estimated evaporation first pond area is about 3600 $m^2$by applying a salinity factor of 0.8. The estimated pond recovery is based on the following assumption:
S: 55806 (mg/l), A: 3600 m2, Ws: 5 (m/s), T: 25 ◦c, H: 0.5 (m)

The pond recovery is about 36% which is considered a reasonable value for this sanity range (La Wrence A. H. and Hans P. E., 1970).

ARPN Journal of Engineering and Applied Sciences

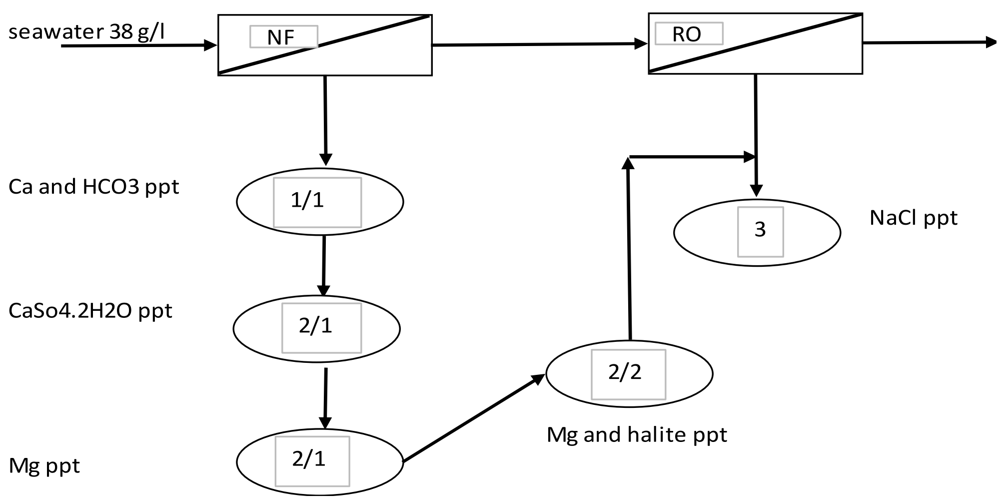

Figure-1. Proposed desalination/brine management scheme.

According to the precipitation sequence of salts, Ca and HCO3 will precipitate in the first evaporation pond cell 1/1, then the concentrated water is directed to another pond cell for additional precipitation of CaSO4. Then the brine water is subjected to the second evaporation pond where Mg compounds precipitate. The main compounds in the first precipitation crystallization cell will be carnallite (potassium and magnesium chloride). Then to the second cell where Mg precipitates as well as halite, the concentrated bittern is then directed to form a combined feed stream to the third pond, with the reject brine from the RO desalination unit. The proposed scheme shows the environmental and cost benefits of applying solar evaporation pond for the disposal of desalination brine in arid and semi-arid regions. The produced salt by this method requires further refining, including drying, crushing, screening and packaging.

CONCLUSIONS

Due to the environmental concerns regarding desalination brine discharge. Solar evaporation pond is a reliable option for brine discharge. A multivariate regression model has been developed to predict evaporation pond recovery. Five parameters have been selected and investigated as the independent variables of the multivariate analysis and one dependent variable which is the pond recovery. These variables are feed TDS value, pond area, wind speed, average temperature and pond depth. It was found that there is a strong relationship between the investigated variables and the pond recovery, the coefficient of determination (R^2) was 0.91. A scheme comprising NF/RO/pond system is proposed as an integrated process for desalination/brine disposal management system.

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