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Use of evaporation ponds for brine disposal in desalination plants

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Abstract

Desalination plants are being used increasingly in inland areas of many countries for supplying water for domestic purposes. If these areas are too far away from the sea, the opportunity to dispose the reject brine (also known as concentrate, reject water, or wastewater) in the ocean no longer exists, given that ocean disposal is the common practice for plants located in coastal areas. Evaporation ponds are especially suitable to dispose of reject brine from inland desalination plants in arid and semi-arid areas due to the abundance of solar energy. In irrigation projects facing a soil salinity problem due to a shallow saline groundwater table, evaporation ponds are also in use. Saline water tables are lowered by pumping or tile draining and the drainage water is stored in evaporation ponds. While evaporation ponds have long been used for salt production in many parts of the world, the disposal of concentrate from desalination plants in inland areas using evaporation ponds is of much significance both economically and environmentally. Guidelines are needed for the design, construction, maintenance, and operation of evaporation ponds for reject brine disposal in an economical and environmentally-sensitive manner. This paper provides a critical review of concentrate disposal technology using evaporation ponds. Relevant topics are also covered including chemistry of brine, brine disposal methods, use of evaporation ponds in agriculture, determination of evaporation rate, and evaporation enhancement methods.

Keywords: Evaporation ponds; Desalination; Inland plants; Brine disposal; Concentrate

1. Introduction

Throughout the world, many communities with limited water resources have witnessed considerable growth in population. Severe water shortages can lead to the deterioration of people's health and may severely constrain the development of the community. A number of such communities have turned to desalination as a solution. In these cases desalination, usually

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recognized as being relatively expensive, has proved to be an affordable and feasible alternative.

Until the early 1960s, the use of desalination processes was very limited in the water industry. Their applications were restricted to activities where almost distilled water was required. Since then, many plants have been erected in various parts of the world for supplying water for various purposes. Based on the process, desalination plants can be categorized into two types. The first involves plants that employ a phase-change process. In such plants desalination takes place while there is a change of phase (i.e., evaporation or freezing). Plants that follow such a process include multi-stage flash (MSF), multi-effect boiling (MEB), vapor compression (VC), solar distillation, and freezing. The second type of desalination plants are single phase. In such plants the extraction of salt takes place while the solution remains in the liquid phase. These include reverse osmosis (RO) and electrodialysis (ED).

One common aspect to both categories of desalination plants is the production of concentrate. The amount of concentrate as a percentage of the feed water varies depending on the choice of method, initial salinity of feed water, and factors affecting the choice of disposal method. Awerbuch and Weekes [1] reported that brackish RO plants, in general, produced 25% of the total feed water flow as reject brine. They described the use of evaporative brine concentrators to reduce the RO reject brine to 2% of the overall flow. According to Alaabula'aly and Al-Saati [2], groundwater RO plants typically produce a brine stream of 10–25% of the feed. Thermal processes such as MSF and MEB have relatively low water recoveries. The concentrate from thermal processes is typically mixed with cold water prior to discharge. The dilution of concentrate results in a final discharged effluent that is rarely more than 15% higher in salinity than the receiving water [3]. Other wastes produced by desalination plants (e.g., cleaning wastes) are either mixed with the concentrate or stored separately to be disposed of later.

The disposal of wastes from inland plants must be addressed. Otherwise serious issues will develop as the numbers of inland plants increase and expensive remedial measures will have to be taken to rescue the delicate ecosystems into which the brine will be discharged [4]. In this paper a critical review of concentrate disposal technology using evaporation ponds is presented. Special focus is placed on the chemistry of brine, brine disposal methods, use of evaporation ponds in agriculture, determination of evaporation rate, and evaporation enhancement methods.

2. Chemistry of concentrate

The characteristics of reject brine (concentrate) are directly related to the quality of the feed water, the desalination technology used, the percent recovery, and the chemical additives used. Khordagui [5] presented the chemical properties of reject brine from some Gulf region desalination plants (Table 1). Mickley et al. [3] classified wastes generated by the different components of the membrane desalination process into the following categories: pretreatment waste, membrane concentrate, cleaning waste, and post-treatment waste.

In RO systems, especially in plants that produce drinking water, pretreatment may consist of acidification, addition of anti-scalant chemicals, chlorination, and de-chlorination. For poor quality water, filtration, coagulation, flocculation, ion exchange, and carbon adsorption may also be used. All these processes generate wastes that are removed before the membrane process starts.

Membrane concentrate is primarily a concentrate of the feed water that includes the raw water along with the added chemicals for pretreatment purposes. If post-treatment is done on the

Table 1
Characteristics of reject brine water from some desalination plants in the Gulf region (after Khordagui [5])

Parameters	Abu-fintas Doha/Qater seawater	BWRO Ajman	BWRO Um Quwain	Qidfa I Fujairah seawater	Qidfa II Fujairah seawater
Temperature, °C	40–44	30.6	32.4	32.2	29.1
pH	8.2	7.46	6.7	6.97	7.99
Electrical conductivity	NR	16.49	11.33	77.0	79.6
Ca, ppm	1300–1400	312	173	631	631
Mg, ppm	7600–7700	413	282	2,025	2,096
Na, ppm	NR	2,756	2,315	17,294	18,293
HCO_3, ppm	3900	561	570	159	149.5
SO_4, ppm	3900	1,500	2,175	4,200	4,800
Cl, ppm	29,000	4,572	2,762	30,487	31,905
TDS, ppm	52,000	10,114	8,276	54,795	57,935
Total hardness, ppm	NR	NR	32	198	207
Free Cl_2, ppm	Trace	NR	0.01	NR	NR
SiO_2, ppm	NR	23.7	145	1.02	17.6
Langlier SI	NR	0.61	0.33	NR	NR
Cu, ppb	<20	NR	NR	NR	NR
Fe, ppb	<20	NR	NR	NR	NR
Ni, ppb	Trace	NR	NR	NR	NR
Antiscale, ppm	0.8–1.0	NR	NR	NR	NR
Antifoam, ppm	0.04–0.05	NR	NR	NR	NR

NR, not reported.

concentrate, its characteristics are further affected. Mickley et al. [3] reported on concentrate quality from some membrane drinking-water plants in Florida. The tests they used revealed a total of 40 different inorganic chemicals.

Chemical concentrations in the concentrate depend on the membrane system recovery and the membrane rejection of a particular chemical. The concentrate from membrane desalination processes is characterized by high total dissolved solids (TDS) and has minimal amounts of process-added chemicals. In general, raw water quality determines the final concentrate quality. The degree of concentration, also called the concentration factor (CF), is defined as:

$$CF = \frac{1}{1-R} \quad (1)$$

where R is the fractional recovery. The above relationship is valid for chemicals that are completely rejected by the membrane but is a good approximation for most chemicals in brackish and seawater RO systems.

Alaabdula'aly and Khan [6] analyzed the feed, permeate, and brine waters of four groundwater RO plants in the central region of Saudi Arabia for 12 metals (Al, As, Ba, Cd, Cr, Fe, Mn, Ni, Pb, Se, and Zn). Nickel and copper were found to be absent in all samples. All other metals were found to be within the limits prescribed by WHO for drinking water. Rao et al. [7] described a case study in India where seepage from reject brine caused contami-nation of groundwater of the source well and resulted in abnormal increase in hardness of the groundwater.

3. Brine disposal methods

Reviewing the characteristics of brine disposal from desalination plants, Koening [8] noted that brine disposal is in a different category than sewage disposal. He also stated that there is no way to reduce brine to simpler and harmless compounds as they are already the simplest of inorganic compounds. He went on to say that no good way exists to reclaim the carrying water from the dissolved solids, for if there were, it could be used in the desalting process. While the quantities of materials are very large, Koening [8] emphasized that these materials do not look attractive economically.

Guidelines issued by the US Federal Water Pollution Control Administration [9] for disposal systems in the USA emphasize that such systems must comply with federal, state, and local regulations; avoid pollution, lawsuits, and be in good engineering practice; be capable of adequately taking care of all the effluents continuously over the life of the plant; not unduly harm the land, surface, and underground fresh water sources, sheltered bays and estuaries, or the seas; and not contaminate the feed water intake or future resources. In the Gulf countries most of the large-scale desalination plants are located on the coastline. These plants discharge their concentrate into near shores. Khordagui [5] and the SWCC [10] looked into this issue in a comprehensive manner. Desalination industry experts have accepted the fact that the ocean brine disposal method is the least expensive method. They argue that rapid mixing and dilution makes it a "safe" disposal option. Mandil [11] observed that the environmental impact of brine discharge is related to the physical, chemical, and biological characteristics of the receiving marine environment. The recovery ratio, or the amount of feed water that must be provided to the plants for each unit of product water, has significant environmental implications. The higher the recovery ratio, the greater the salinity of the concentrate.

Khordagui [5] supported the practice of ocean brine disposal with the argument that the amount of seawater withdrawn for desalination is relatively minute when compared to the water mass of the open sea. He stated that the amount and nature of salts discharged with the brine are identical to the salt content of the open sea, with the concentration factor increasing by no more than two. In order to avoid recirculation of plant effluents to the intakes of the desalination plants, Khordagui [5] emphasized that the outlets should be specifically engineered to discharge in coastal areas where maximum circulation patterns and hydrographic currents can easily disperse and dilute the brine. On the other hand, Del Bene et al. [12] concluded that dense brine discharge into the ocean can impact the benthic environment.

4. Disposal from inland plants

Various options exist for the disposal of reject brine from inland desalination plants. These include waste minimization, discharge to surface water, discharge to wastewater treatment plants, deep wells, land application, evaporation ponds, and wastewater evaporators.

Khordagui [5] identified the following options for disposal of reject brine from inland RO desalination plants: pumping into specially designed, lined evaporation ponds; deep-well injection; disposal into surface water bodies; disposal through pipelines to municipal sewers; concentration into solid salts; and irrigation of plants tolerant to high salinity (halophytes). Mickley et al. [3] identified the factors that influence the selection of a disposal method. These include volume or quantity of concentrate, quality or constituents of concentrate, physical or geographical location of the discharge point of the concentrate, availability of receiving site, permissibility of the option, public acceptance, capital and operating costs, and ability for the facility to be expanded. They also presented a survey of drinking water plants in the continental US (for drinking water membrane plants having a capacity of 98 m^3/d or more) that included 137 plants where 48% dispose of the concentrate to surface water, 23% dispose to the head-works of wastewater treatment plants, 12% utilize a land application process, 10% dispose via deep well injection, and 6% use evaporation ponds.

According to the ESCWA [13], cost plays an important role in the selection of a brine-disposal method. The cost of disposal ranged from 5–33% of the total cost of desalination for all methods. The cost of disposal depends on the characteristics of reject brine, the level of treatment before disposal, means of disposal, volume of brine to be disposed of, and the nature of the disposed environment. Glueckstern and Priel [14] found that the disposal costs of inland RO desalination plants are higher than that of plants disposing reject brine in nearby seas or lakes.

Waste minimization is an approach in which the objective is to produce less concentrate (generally by membrane-process recovery-enhancement techniques) or to reduce the concentrators prior to ultimate disposal [3]. This particular approach is not usually very economical since the increase in cost is substantial, given the need for an extensive pretreatment and the increased membrane area. Although the volume is reduced, the concentration of various minerals and chemicals increases. Such high concentration can create special problems with disposal since many disposal regulations are based on concentrations, not volume.

By discharging into surface water (where available), the brine is diluted. The increase in concentration of minerals and salts due to brine disposal into large bodies of water is insignificant if the volume of reject brine is not large (relative to the volume of surface water). The self-purification capacity of the receiving water is an important consideration. This capacity must not be exceeded when brine disposal is made. Disposal into surface water bodies can be permitted only if such discharges will avoid any detrimental impact on environmentally-sensitive areas.

Squire et al. [15] described a method of surface water disposal of RO membrane concentrate by blending the concentrate with backwash water from sand filters. Many small RO plants dispose their reject brine in municipal sewerage systems. This process has the attraction of lowering the BOD of the domestic sewage. However, the increase in TDS may have some effects on the microorganisms of the system and may make the treated effluent unsuitable for irrigation purposes. Moreover, the disposed reject brine may overwhelm the existing capacity of the sewerage system. The recovery of mineral salts from reject brine was looked into by different researchers [16]. This option will prove to be attractive only if the cost of production is economical. Irrigation of salt-tolerant plants by reject brine will be possible provided soil salinization is maintained at an acceptable level and the potential risk to groundwater is minimal.

Deep injection wells (depths ranging from 330–2,600 m) can be used to inject liquid wastes in porous subsurface rock formations. Site selection, which is dependent upon geological and hydrogeological conditions, is extremely important in the design of injection wells. Such wells, for example, should not be located in areas vulnerable to earthquakes or regions with mineral resources. Another consideration in the design and operation of such an option is the non-movement of wastes into or among underground sources of drinking water. As such, site selection is the most important step in the development of an injection well.

Disposal of reject brine by mechanical evaporation is a costly process. In plants where a zero-liquid discharge concept is in practice, mechanical evaporators are used. Costs are high due to the high energy consumption and costs required for final salt or brine disposal.

Single-effect evaporators or vapor compression evaporators are widely used for mechanical evaporation.

Irrigation systems, percolation ponds, and infiltration trenches can also be used for disposal purposes. For irrigation, the quality of reject brine must satisfy crop and soil requirements. The presence of high concentrations of exchangeable sodium or trace elements can render reject brine unsuitable for irrigation purposes. Mickley [3] listed the following design criteria applicable to irrigation with reject brine: site selection, pre-application treatment, hydraulic loading rates, land requirements, vegetation selection techniques, and surface runoff control.

5. Use of evaporation ponds

Evaporation ponds have been used over the centuries to remove water from saline solution. Mickley et al. [3] listed several advantages for disposal of reject brine using evaporation ponds. They stated that evaporation ponds are relatively easy to construct, while requiring low maintenance and little operator attention compared to mechanical systems. They added that no mechanical equipment is required in evaporation ponds, except for the pump that conveys the wastewater to the pond. Finally, they emphasized that evaporation ponds are frequently the least costly means of disposal, especially in areas with high evaporation rates and low land costs. Mickley et al. [3] also listed some disadvantages including the need for large tracts of land when the evaporation rate is low or the disposal rate is high, the need for impervious liners of clay or synthetic membranes such as PVC or Hypalon, and the potential of contaminating underlying potable water aquifers through seepage from poorly constructed evaporation ponds.

Evaporation ponds can be successfully used as a disposal method especially in countries with dry and warm weather, high evaporation rates, and availability of land at low cost. Sealing of evaporation ponds reduce the risk of groundwater contamination. Truesdall et al. [17] observed that evaporation ponds were used in some of the small desalination plants in the US. Evaporation ponds ranging from 13.6 to 34.3 ha are used for disposal purposes in the desalination plants in the central region of Saudi Arabia [2]. Mickley [18] considers evaporation ponds most appropriate for relatively warm and dry climates with high evaporation rates, level terrain, and low land costs.

Soil salinity is an increasing problem in many parts of the world. In Australia, over 150,000 ha may be affected by salinization associated with irrigation and additional 2,000,000 ha may be affected by dry-land salinization in the Murray Darling Basin alone [19]. One way to control soil salinization is to lower the saline groundwater table through groundwater pumping. The pumped groundwater can be put in disposal basins that can be either evaporation or holding basins. Holding basins are used for effluents with low salinity. Therefore, these effluents may be reused with or without prior treatment or dilution. Evaporation basins are designed to concentrate the received effluent and reduce its volume through evaporation. The Murray Region of Australia includes more than 150 basins for evaporative disposal of large volumes of groundwater and saline surface drainage. However, no standard design appears to have been followed in the construction of disposal basins. Some of the basins are natural basins (i.e., no lining or compaction). Most of the constructed basins are small (not exceeding a few hectares). When designing evaporation ponds, it is best if a number of smaller ponds are constructed and connected by a pipeline. Smaller ponds are easy to manage especially in windy conditions where wave action can damage the levees requiring costly maintenance. Suitable site selection is very important. Unlined ponds located in light soils will leak resulting in the movement of salts to the groundwater.

Large public schemes require extensive operation and maintenance investment. The biggest cost is transporting effluent to the disposal site. Pumping saline water, which may have high dissolved gas levels (leading to cavitation in pipes) or iron sludge (due to the presence of iron bacteria), can cause rapid deterioration of the screens, pipes, and pumps. Once in the evaporation basin, moving the concentrate from bay can be labor-intensive, particularly if active salt pro-duction is required. Other maintenance includes erosion control, wildlife management, and seepage control.

Evaporation ponds are designed to concentrate effluents. Therefore, they aim to reduce effluent volume by evaporation, occasionally producing salt as part of the process. Hoxley [20] developed a rating system to evaluate disposal basins in terms of basin size, ratio of inflow volume to evaporative capacity, potential for leakage to groundwater, ownership and monitoring fre-quency, existence of re-use, and other factors. Realica and Williams [21] also reviewed evaporation basins in New South Wales, Australia, using these criteria. They focused on determining the effective hazard of using evaporation basins. The information in both publications can be used to identify disposal basins that are likely to cause environmental hazards. Hostetler et al. [22] produced an interactive GIS database of disposal basins in the Murray Basin in Australia. The database also includes scanned images of air photos, Internet-accessible documentation, and software downloads.

As with most engineering structures, there are environmental risks associated with the use of saline disposal basins. The movement of salt (and possibly toxic materials) outside the drainage or salt containment area poses the greatest threat. Following accepted engineering standards will minimize the risks while management and decommissioning plans will increase confidence that basin operators are minimizing environmental risks.

The use of evaporation basins is at times emotive, especially for some farmers whose lands are adjacent to these basins. However, evaporation basins remain in many cases the most cost-effective means of saline water disposal. By concentrating the saline "waste", evaporation basins also offer an opportunity to develop resource recovery measures such as aquaculture, brine shrimp, beta-carotene production, salt harvesting, recovery of bitterns, and linking to solar ponds for electricity generation. While research for many of these beneficial uses is at an early stage, it is important not to lose sight of the opportunities that can develop from scientific management of evaporation basins.

6. Design considerations of evaporation ponds

Mickley et al. [3] stated that the proper sizing of an evaporation pond depends on accurate calculation of the annual evaporation rate, as evaporation ponds function by transferring liquid water in the pond to water vapor in the atmosphere above the pond. Higher evaporation rates will require smaller-sized ponds. Pond size includes two components: surface area and depth. The evaporation rate determines the surface area whereas the calculation of depth is based on surge capacity, water storage, storage capacity for the salts, and freeboard for rainfall and wave action.

Evaporation rates can be determined using various methods. A standard evaporation pan (class A pan) is widely used to measure pan evaporation rates. The latter is multiplied by a pan coefficient to determine the evaporation rate [23]. Water balance calculations in lakes can also be used to estimate likely evaporation rates from ponds.

Salinity of water influences the rate of evaporation. As the salinity increases, evaporation decreases. Mickley et al. [3] suggested the use of evaporation ratio of 0.7 for multiplying calculated solar evaporation rate to incorporate the effect of salinity. They also suggested that pond depths ranging from 25 to 45 cm are optimal for maximizing the rate of evaporation. Very shallow evaporation ponds are subject to drying and cracking of the liners. An ideal evaporation pond must be able to accept reject brine at all times under all conditions. Freeboard for rainfall is to be estimated on the basis of rainfall intensity and duration. Freeboard for wave action is based on the wave height likely to be produced in the pond. Standard formulas are available for such calculations [24].

Accurate evaporation data are required for designing an efficient evaporation pond. In addition, one must ensure that the average annual evaporation depth exceeds the depth of water that would have to be stored in the pond. One must also remember that the rate of evaporation varies from location to location.

The following formula was proposed for calculating the open surface area of the evaporation pond:

$$A_{\text{open}} = \frac{V_{\text{reject}} f_1}{E} \qquad (2)$$

where A_{open} is the open surface area of evaporation pond (m^2), V_{reject} is the volume of reject water (m^3/d), E is the evaporation rate (m/d), and f_1 is a safety factor to allow for lower than average evaporation rates.

During the winter, the pond tends to store the reject water. The minimum depth required to store the volume of water is calculated using the formula:

$$d_{\min} = E_{\text{ave}} f_2 \qquad (3)$$

where $d_{\min}$ is the minimum depth (m), E_{ave} is the average evaporation rate (m/d), and f_2 is a factor that incorporates the effect of the length of the winter. A freeboard (defined as the depth above the normal reject water surface) must be provided so that rainfall and periods of abnormally low evaporation do not cause reject water to spill out of the pond. A freeboard of 200 mm is recommended.

In general, the walls of ponds are constructed above the ground level. A controlled spillover facility is also needed as an integral part of the evaporation pond. This facility accommodates any spilled water from the pond. Liners are the most important feature of an evaporation pond. They should be mechanically strong and impermeable. All liners must be strong enough to withstand stress during salt cleaning. Sometimes sands can be placed over liners to facilitate salt removal. Sealing of liner joints is crucial as leakage usually takes place along joints. A subsurface drainage system should also be installed to remove the leaked wastewater. In the course of time, salts deposited in ponds must be removed. Options for safe disposal of salt deposits include their sale to interested buyers, disposing of the salt to the sea, or the disposal of the salt to an approved waste disposal site.

Basins used for disposal can be natural basins (to take advantage of the natural depression in the earth's surface), modified natural basins, or constructed basins excavated from the ground. The natural basins include saline lakes, billabongs, salinas, or dry natural depressions. Figs. 1 and 2 represent small evaporation ponds at a farm scale. Their size does not exceed a few hectares (the largest being 10 hectares). It is best if a number of smaller ponds are constructed adjacent to one another and connected by a pipeline placed no more than 30 cm above the bed

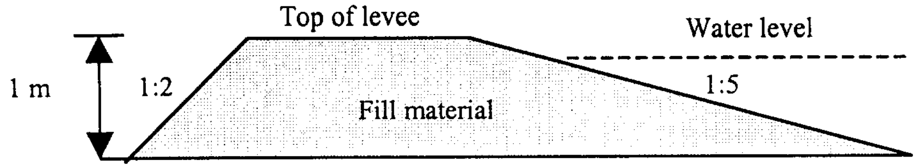

Fig. 1. Generalized embankment dimensions.

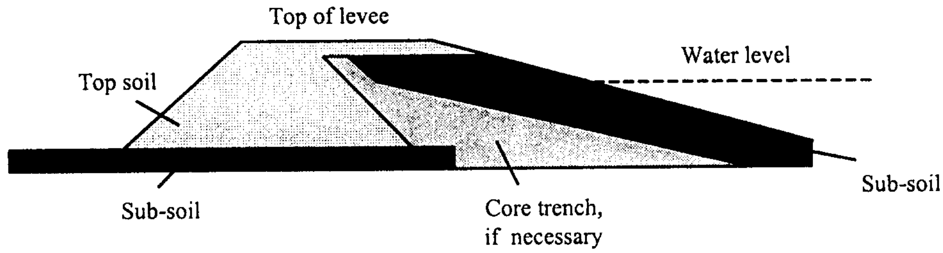

Fig. 2. Cross-section of embankment.

of the pond. Smaller ponds are easy to manage especially in windy conditions where wave action can damage the levees, thereby increasing maintenance costs. The length of the pond should be placed at right angles to the predominant direction of wind to dissipate wave damage. This is particularly important if the pond is plastic-lined.

Suitable site selection is very important. Ponds located in light soils will leak, resulting in the movement of salts to the groundwater. In such cases plastic linings or other treatment will be needed to reduce soil permeability. Banks should be 1 m in height and 2.4 m wide at the crest to allow for the movement of light vehicles. To minimize bank erosion, an inside slope of 1:5 is recommended (see Fig. 1). This will absorb much of the wave energy. The outside bank can be constructed at a 1:2 slope. Before construc-tion, the topsoil where the bank is to be located should be removed. If the site contains good impermeable clay to a depth of 3 m or more, then the top 0.5 m can be used to form the banks. The topsoil can then be pushed against the outside banks to encourage cover by vegetation. This will reduce erosion in low-salinity disposal areas. The banks should be compacted during construction using a sheepsfoot roller. Laser leveling of the bed will increase evaporation by gaining even spread of water. As an additional precaution to control lateral seepage, a small diameter inter-ception well may be installed along the perimeter of the ponded area and the effluent pumped back into the ponds. Additional guidance on small scale (less than 100 ha) salt disposal basins is given in Jolly et al. [25].

7. Construction, operation, and maintenance of evaporation ponds

Evaporation ponds for disposal of concentrate from desalination plants need to be constructed as per the design and maintained and operated properly so as not to create any environmental problem, especially with regards to groundwater pollution. It has been suggested that it is unnecessary that evaporation ponds remain wet at all times. It is more sensible to ensure that the average annual evaporation rate exceeds the depth of water that would have to be stored in the pond.

Evaporation ponds are constructed along a basic pattern of a series of shallow concentrating ponds followed by crystallization ponds. The main problems centered around finding the best operating depth of pond as well as the number and size of ponds [26]. Large ponds tend to have excessive depths along one side and the control of wave action becomes a problem [27]. Evaporation ponds designed to prevent leakage must have impervious linings or be provided with seepage-collection systems.

It has been recommended that no salt should be removed from the pond for the first year or two of operation so that a hardpan is permitted to develop at the base of the pond. This hardpan can only develop if the pond completely dries out during the hottest periods of the year. Salt should be removed during the dry months. If salts are left in the pond for extended periods of time, the storage volume is reduced and spillover can take place. For a given salinity, Fig. 3 provides an estimate of precipitate produced for each foot of wastewater discharged to the pond.

Evaporation-pond liners need to be installed in accordance with manufacturer's instructions. Sealing adjacent sections of the liner must be done properly. However, it may be unnecessary to reduce leakage/seepage to the same extent in

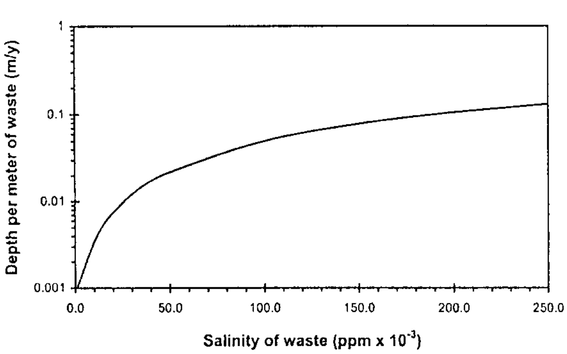

Fig. 3. Depth of precipitate (adapted from USDI [28]).

all circumstances. Soil conditions, geologic substructure, plant operation schedule, and the desired life of the pond must be considered in making a decision [28]. The ponds should be monitored regularly. It is recommended that both the volume of reject brine into the evaporation pond and water levels in the pond are recorded on a continuous basis. Also the levels of groundwater and salinity adjacent to the ponds should be regularly monitored. Reporting based on monitoring data and relevant operation and maintenance information is also an important step in the management of disposal systems of desalination plants.

8. Surface disposal of brine and pollutant movement through the soil

Assessing the extent and rate of pollutant movement through the soil profile from the disposed brine of inland desalination plants is extremely critical. It provides a means for addressing the water quality issues associated with the deep percolation of the rejected brine when this by-product of desalination is discharged improperly. In addition, understanding the movement of the concentrated brine along with heavy metals is essential in evaluating their negative impacts on the environment and addressing the regulatory aspects of brine reject discharge.

Models that describe the physical, chemical, and biological processes associated with the movement of solutes in the soil profile have been derived and investigated by many researchers [29–31]. According to Addiscott and Wagenet [32], such models range from being deterministic, where individual processes are defined mathematically, to stochastic, where the emphasis is less on the process but more on predicting the statistical distribution of a given characteristic. The former category of models is usually complex in nature as it emphasizes the processes involved and the interactions among these processes. They often include partial differential equations that must be solved numerically, rather than analytically.

Campbell [33] presented the basic equations describing the transport of solute through the soil profile. He classified them into soil interacting and soil non-interacting solute transport equations. The first situation represents a mass flow process where the solutes are assumed to be totally dissolved in water and transported through convection without dispersion. This represents a simplified approach to solute transport within the soil profile where the change in concentration of a solute moving by steady-mass flow is described by the following equation [33]:

$$\rho_b \frac{\partial S}{\partial t} = q \frac{\partial S}{\partial z} \tag{4}$$

where ρ_b is the soil bulk density ($M.L^{-3}$), S is the solute present per mass of soil ($M.M^{-1}$), t is time (T), q is the water flux density ($M.L^{-2}.T^{-1}$), and z is the soil depth (L). Using the above equation and assuming that the flow velocity of the solution in the soil profile is uniform, this form of solute transport movement is termed piston flow. The term S combines the solution and sorbed components of the solutes present per mass of soil. It can be expressed as

$$S = N + \theta_m c \tag{5}$$

where N is the sorbed chemical per mass of soil ($M.M^{-1}$), θ_m is the water content of the soil on mass basis ($M.M^{-1}$), and c is the solute concentration in the soil solution ($M.M^{-1}$).

An alternative equation for modeling the transport of solutes in the soil profile incorporates the movement of solutes due to hydraulic and concentration gradients [33]. This equation is referred to as the convection-dispersion equation. It can be developed by combining the convection and dispersion fluxes to determine the total flux of solutes [34]. The resultant equation is expressed as follows:

$$\rho_b \frac{\partial S}{\partial t} = \frac{\partial \left[\rho_w D(\theta,q) \frac{\partial c}{\partial z} \right]}{\partial z} \tag{6}$$

where ρ_w is the density of water ($M.L^{-3}$), D is a diffusion coefficient ($L^2.T^{-1}$) that includes both molecular diffusion and hydrodynamic dispersion, and θ is the volumetric water content of the soil ($L^3.L^{-3}$).

Both piston flow and convection-dispersion equations are time-dependent one-dimensional partial differential equations that cannot be solved analytically. Approximate numerical solutions, using the finite difference or finite element methods, are usually employed in solving these equations after incorporating the appropriate boundary conditions. The resultant systems of equations are non-linear, requiring the implementation of iterative solutions. Although the presented one-dimensional equations are widely used in modeling solute transport in the soil profile, many problems require the solution of two- and three-dimensional differential equations. Again, these equations must be solved numerically after employing iterative solution schemes, given the non-linear nature of the equations. Surface disposal without any surface barrier and the consequent solute movement in the unsaturated zone before solutes reach the water table can be assessed using such models. Likewise, leakage from evaporation ponds can be analyzed using the same approach.

9. Determination of evaporation from brine

Evaporation rates from large freshwater bodies are dependent on many factors such as wind speed, temperature, and vapor pressure. Two main approaches exist for determining evaporation. These include the energy budget and mass transfer methods. In the former method the conservation of energy principle is used while estimating the amount of energy needed to change water from the liquid to the vapor phase. The energy used in evaporation of a liquid can be expressed as:

$$Q_e = E \rho L \tag{7}$$

where Q_e is the energy used in evaporation (W/m^2), E is the rate at which water is evaporated (mm/d), ρ is the mass density of the evaporated liquid (kg/m^3), and L is the latent heat of vaporization at the liquid surface temperature (KJ/kg).

In the mass transfer method the mechanism of removal of fluid vapor is by diffusion. This method is built around the well known Dalton's formula on the rate of vaporization of liquid into gas [23]. The method is expressed as

$$E = C_1 \left(e_w - e_a\right) \tag{8}$$

where E is the evaporation rate (mm/d), C_1 is an empirical coefficient, e_w is the partial pressure of liquid (mm of Hg), and e_a is the partial pressure of air (mm of Hg).

Another approach for estimating the evaporation rate utilizes the water budget method that is based on the law of conservation of mass where the inflow into and out of tank or pond are tracked. However, the most widely used method for determining evaporation is based on measured pan evaporation. A multiplying factor (pan coefficient) is used to convert pan evapo-ration from surface water bodies. Many factors influence both evaporation from pans and the coefficient to be used for conversion. Dissolved solids reduce vapor pressure of the solution resulting in lower evaporation.

USDI [28] was one of the earliest investigations in this field where it was reported that the ratio of brine evaporation to that of distilled water decreased about 1% for each increase of 0.01 in specific gravity. They also reiterated the conclusion reached by Harbeck [35] who stated that the salinity in water reduces evaporation. However, Harbeck [35] stated that it was difficult to derive a simple expression for the effect of salinity on evaporation due to the many interrelated variables involved.

Since the volume of waste is minimized by evaporation, increasing the evaporation rate would enhance the volume-reduction process in evaporation ponds. This would result in reduced pond size leading to savings in construction costs. Evaporation rates can be increased by raising the water temperature, exposing more water surface area by spraying into the atmosphere, increasing the vapor pressure difference between the surface and atmosphere, reducing surface tension or the bond between water molecules, increasing the exposed surface area, increasing the wind velocity and ground air layer turbulence, increasing the surface roughness, and stirring the pond [36].

Pond depth appears to have some effect on evaporation. USDI [36] reported on contradictory research results on this issue. Some research showed faster evaporation rates at shallow depths whereas others concluded that deep ponds were more effective in enhancing the evaporation rate. Kingdom [37] investigated the concept that suitable molecules absorbed on the surface of water may increase the rate of evaporation by forming weaker hydrogen bonds with water.

The evaporation rate can be enhanced by increasing the water temperature using a suitable dye. USDI [38] reported that the addition of Naphthol Green dye increased the evaporation rate by 13%. The dye was added at a concentration of less than 2 ppm. However, the cost of dyes is the major constraint in the application of this method. Smoak [39] investigated the spraying method for evaporation enhancement of fresh water. He reported a 17–60% increase in the rate of evaporation under a pilot experimental field.

10. Conclusions

The subject of concentrate disposal technology using evaporation ponds was critically reviewed. The topics covered, among others, include brine disposal methods, use of evaporation ponds in agriculture, evaporation pond design considerations, surface disposal of brine and pollutant movement through the soil, and evaporation rate determination and enhancement methods. It was evident that there are economic and environmental imperatives for proper disposal of reject brine from inland desalination plants using evaporation ponds. The latter can be successfully used as a disposal method especially in countries with dry and warm weather, high evaporation rates, and availability of land at low cost. Typically, arid and semi-arid areas are environments where evaporation ponds can be successfully used for disposal of reject brine from inland desalination plants.

The last 20 years have seen rapid growth in the number of desalination plants for producing drinking water in many parts of the world. Unfortunately, the environmental implications associated with the discharge of concentrate from desalination plants have not received adequate considerations by concerned authorities. The likelihood of causing environmental problems from desalination plants in inland areas is much greater as concentrates are mostly disposed of on land. Improperly designed and managed disposal systems have the potential of contaminating groundwater resources. While RO plants in inland areas produce concentrate of high salinity, such plants are not usually associated with the presence of residual chlorine, heavy metals, and the problem of thermal pollution. In addition, the salinity of concentrate from RO plants in inland areas is much lower than that of seawater plants.

The cost of disposal of reject brine from inland desalination plants can be quite substantial. However, there is an urgent need to find cheaper but environmentally-friendly methods of disposal. This will ensure that good-quality drinking water can be supplied to areas of water shortages where desalination remains the only viable option. Evaporation ponds, when properly designed and managed, can be a viable means for disposal of brine from desalination plants, especially in inland areas. Evaporation ponds have also long been used for salt production in many parts of the world. In irrigation projects facing soil salinity problem due to a shallow saline groundwater table, evaporation ponds have been widely in use. Water tables are lowered by pumping or tile-draining and the drainage water is stored in evaporation ponds.

Evaporation ponds are usually the least costly means of brine disposal in areas with high evaporation rates and low land costs. However, seepage from poorly constructed evaporation ponds can contaminate underlying aquifers. Contamination of feed water sources is also likely if the reject brine is improperly disposed, on the surface close to inland desalina-tion plants.

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