BIOLOGICAL AND PHYSICAL MANAGEMENT INFORMATION FOR COMMERCIAL SOLAR SALTWORKS

JOSEPH S. DAVIS

Department of Botany,University of Florida
Gainesville, Florida 32611
e-mail: jsd@botany.ufl.edu

EXTENDED ABSTRACT

A solar saltworks (salina, saltfield) is a connected series of concentrating ponds through which seawater flows, evaporates, and delivers brine nearly saturated with sodium chloride to crystallizer ponds where salt is deposited. After harvest, the salt is washed, stockpiled and marketed. In every pond these physical phenomena are intimately linked to biological processes. Design of a saltworks that enables physical systems to operate in harmony with biological systems in the ponds results in enhanced evaporation, low losses of salt in the harvest, wash and stockpiling processes, harvest of crystals mostly large and clear at design capacity, marketed salt of world quality, and prolonged life of the saltfield. These results are rarely achieved because design and operation of many solar saltworks are unable to allow the biological system (that inevitably develops in every pond) help rather than harm salt production. This report reviews design concepts, features and management techniques that enable microorganisms dwelling in the ponds of salinas to aid salt production, mitigate disasters, and permit continuous and economic manufacture of high quality salt at design capacity.

Attributes of biological systems that aid salt production include development and maintenance of microorganisms suspended in the water (planktonic communities) of maximum species diversity at each salinity range, which power and control the living organisms at desired levels, and aid evaporation. Characteristics of benthic communities favorable to salt production include development and maintenance of mats firmly attached to pond floors that sustain desired thicknesses, preserve biodiversity, remove and permanently sequester nutrients from the overlying water, and control leakage and infiltration.

Salina design that enables development and maintenance of biological systems favorable to salt production requires site selection based on integration of information on ecology, climate, geology, and soil characteristics of the intended saltworks area. Subsequent construction and operation of the saltfield involve use of this information to enable pond layout matched to the local environment; selection of appropriate numbers, sizes and circuits of ponds; provision to maximize control of depths and flows to maintain salinity constant at each point in every concentrating pond; provision to favor development of planktonic or benthic communities in concentrating ponds; and provision to maximize brine utilization fed to crystallizers. Management of the completed project also requires continuous collection, display and utilization of information that indicates the physical and biological status of the saltfield, efficiency of the harvest and wash processes, and concentrations of critical ions and insolubles in the washed salt. This information allows manipulation of control features to make routine adjustments, anticipate and obviate developing problems, and enable optimum and harmonious performance of the physical and biological systems.

Keywords: *Aphanothece halophytica*, biological management, *Dunaliella salina*, *Lamprothamnium*, *Ochromonas*, solar saltworks,

1. INTRODUCTION

Solar saltworks (salterns, saltfields, salinas, solnitzi) use energy from wind and sun to evaporate seawater, inland brines, or subterranean saline water in a connected series of shallow (40- to 70-cm) concentrating ponds and deposit salt (sodium chloride) or other valuable products in crystallizer ponds (crystallizers) for commercial purposes. Sodium chloride produced from seawater is the chief or only product of most solar saltworks, but potassium sulfate, potassium chloride, sodium carbonate and other salts may be manufactured.

In the concentrating ponds of saltworks manufacturing sodium chloride, a salinity gradient is established as the intake seawater evaporates and flows downstream, salts of low solubility (in respect to sodium chloride) first precipitate as calcium carbonate, and later as calcium sulfate (gypsum). After becoming nearly saturated with sodium chloride, brine repeatedly flows into crystallizers where evaporation continues, salt is deposited on the floors, and the supernatant liquid (bittern) periodically removed until 5 cm to 20 cm of salt accumulates. The supernatant, rich in magnesium and potassium chlorides and sulfates, is drained away before harvest, the salt is removed by mechanical equipment, washed to decrease contaminants, stockpiled for a time to further decrease contaminants and water levels, and then marketed. By this process the purity of salt may exceed 99.7% on a dry basis.

Solar saltworks provide an important and environmentally friendly source of sodium chloride; saltfields account for more than one third of the worldwide production, much of the energy for manufacture is without cost, and the demand for the product has been increasing directly with the expanding human population (Brown 2000).

The three major types of solar saltworks are the continuously operated, the seasonally operated, and the artisanal saltfields. The first two are fully mechanized, use modern techniques and instrumentation for brine control, and manufacture from less than 100 thousand tons per year to more than 7 million tons annually; the salt is produced mainly for the chloralkali process. Most artesanal saltworks are small and labor intensive, use traditional brine control methods, and are harvested frequently by hand with rakes and shovels. The salt is produced directly for human consumption.

Continuously operated solar saltworks require dry climates with low annual rainfall. They maintain a desired salinity gradient in their ponds during the entire year and harvest one or more times in a 12-month period. Typically, these salinas maintain salt floors in their crystallizers consisting of a 4- to 15-cm layer of sodium chloride above which the crop is deposited. The salt floor promotes crops nearly free of insoluble substances and supports heavy grading, harvest, and hauling machinery.

Seasonal saltworks exist either in mild climates with moderate rainfall distributed throughout the year, or in Mediterranean climates where up to 80% of the annual rainfall and/or snow are limited to off-season months. Both manufacture salt only during the best evaporation seasons. Because of rainfall and snow, seasonal salinas are unable to maintain salt floors in their crystallizers. Instead, they harvest at the end of the production season salt deposited on compacted native soils. In the off-seasons of the seasonal salterns in moderate climates, saltworks that continuously maintain a salinity gradient accept any rainfall, and management officials increase pond depths, decant fresh water from pond surfaces, and decrease or stop flows. With the return of favorable weather and reestablishment of a desired salinity gradient, production begins after saturation with sodium chloride is reached in the crystallizers.

In seasonal saltworks of Mediterranean climates, concentrated brines remaining in ponds after harvest are stored in special deep (~1.5 to 3 m) reservoirs within or away from the circuit of ponds where dilution from rainfall or snow will be low, and any freshwater on the surface of these ponds is carefully decanted as required. At the beginning of the next production season, dilute water accumulated in the shallow ponds is drained and the salinity gradient is reestablished with seawater. The stored concentrated brines are distributed to appropriate ponds (Davis 2000).

Salinas may consist of a single series of directly connected ponds, or they may be composed of several parallel series whose brines join at one or more points. The latter arrangement, common in large saltfields, permits maintenance without stopping production of concentrated brine, facilitates control and management, and enables independent flow rates.

Physical phenomena (evaporation, deposition of calcium carbonate, gypsum, and salt) are intimately linked to biological systems, which inevitably develop in every solar saltworks. A biological system composed mainly of microscopic organisms suspended in the water (the planktonic community) and attached to pond floors (benthic communities as mats) can aid (designated a desirable system) or harm salt production (labeled an undesirable system). Desirable systems facilitate attainment of the goal of every saltwoks—continuous and economic production of high quality salt at design capacity. Undesirable systems prevent achievement of this goal.

This paper--based on the author's ongoing worldwide experiences from 1968 to the present at continuously operated, seasonal, and artisanal saltworks, as well as research at saltfield sites and in the laboratory--reviews selected aspects of a successful saltworks with seawater intake. The example continuously and economically produces high quality salt at design capacity. This report also considers commonly encountered problems observed in the field, their causes and successful solutions. Included are causes and effects of troublesome organisms, as well as proven design features and methods to enable physical and biological systems attain goals of their saltworks.

2. DESCRIPTION OF A SUCCESSFUL SOLAR SALTWORKS WITH A FAVORABLE (DESIRED) BIOLOGICAL SYSTEM

This saltworks, with a single series of ponds, has distinct planktonic and benthic communities distributed along three continuous segments of the salinity gradient--low salinity, intermediate salinity, and high salinity—crystallizers where important biological and physical events occur. The nutrient content of the clear intake water, pumped from an area with sparse to occasional marine life, is considered moderate (sensu Javor 2000). The salina is well constructed (with sufficient numbers of ponds to maximize biodiversity, and with dikes which prevent runoff from entering ponds and obviate leakage between ponds), properly managed to establish and maintain a controlled and continuous salinity gradient, and designed to facilitate biological and physical management. Controlled by gates and baffles, back-mixing is absent, wave action slight to moderate, and water depths vary little from the 40 cm to 70 cm range. Located in an environment with low annual rainfall, the salina continuously harvests crops during an entire year from crystallizers with salt floors. In the downstream flow from the intake through crystallizers, areas and volumes of ponds devoted to each salinity range decrease, salinities at each point in the ponds remain unchanging, populations of microorganisms gradually change from low levels of highly diverse groups to assemblages of high concentrations of few kinds, dissolved and particulate organic substances increase, and community metabolism changes from photosynthetic production of organic substances exceeding consumption to consumption surpassing production. At each salinity range, composition and concentration of species remains largely unchanged, sufficient light reaches pond floors to establish and maintain mats, and benthic communities undergo little accretion after a desirable biological system has been established.

The communities in the ponds consist of producer organisms which manufacture the food they require for growth and reproduction from sunlight, carbon dioxide, water and mineral nutrients (this process is photosynthesis). Consumer organisms, the other component of the communities, feed on the producers, other consumers, or their products (e.g., particulate or dissolved organic substances and mucilage). The microscopic, light-requiring producers, colored green, blue-green, yellow, or orange, include certain bacteria, green algae, chrysomonads, cryptomonads, cyanobacteria, diatoms, and dinoflagellates. The seaweeds and seagrasses are also included with the producers.

The consumers include colorless, microscopic bacteria and protozoa, as well as macroscopic brine shrimp and other crustaceans, fly larvae, ostracods, rotifers and worms. Fish, mollusks, prawns, and other large animals present are also consumers.

2.1 Low Salinity Communities: 35 grams of solids per liter 35 PPT to 100 PPT (3.5^{o} to 10^{o} Bé)

In the pond adjacent to the intake, the variety and concentration of microorganisms suspended in the water column, e.g., algae, bacteria, cyanobacteria, flagellates, and protozoa, are similar to the plankton of the nearby marine environment. Seagrasses, seaweeds, fish, and other large marine life are also well represented in the pond. The uppermost 1 mm to 10 mm yellow to green layer of the loosely organized mat (benthic community) includes oceanic plankton that has settled on the floor, as well as protozoa, crustaceans, mollusks, ostracods, rotifers, and worms. The lowermost 1 mm to 20 mm black layer is largely bacteria and organic sediments.

In the downstream ponds of the low salinity range, part of the oceanic plankton dies and releases its contents (nutrients) to a succession composed of salinity-tolerant organisms originating from upstream, and certain species adapted to the increased salinity. This succession process occurs repeatedly to establish communities as the water becomes more saline.

Benthic communities along the remaining ponds of low salinity include rooted seagrasses as well as firm, stratified mats composed of a diverse assemblage of microorganisms. The uppermost 1 mm to 10 mm yellow to yellow-green layer of the mats includes cryptomonads and chrysomonads, diatoms, dinoflagellates, cyanobacteria, ciliates, crustaceans, flagellates, fly larvae, mollusks, nematodes and rotifers. The lowermost 5 mm to 20 mm brown to black layer includes moribund organisms, living bacteria, and organic substances firmly attached to the floor by seagrasses and seaweeds.

Microorganisms in the layered mats remove nutrients from the overlying water and permanently lock them in the benthic community (Davis and Giordano 1996). This sequestration process, aided by fecal pellet production and deposition from grazing crustaceans and filter feeding mollusks, and by settled inorganic and organic substances, prevents reuse of the nutrients by the biological system.

Planktonic communities along the remaining ponds of the low salinity range include microorganisms similar to those of the uppermost layer of the benthic communities, which may become suspended by wind and wave action. Suspension of organisms and flocculents may temporarily change the water from clear to slightly turbid.

2.2 Intermediate Salinity Communities: 100 PPT to 210 PPT (10^o to 18^o BÉ)

Communities in this range consume more organic substances than they produce; the biological system is maintained by photosynthetic organisms in the ponds and by exports from upstream. In ponds of the first half of the range, the water becomes turbid from suspended calcium carbonate. The producer plankton includes low concentrations of a diverse group of unicellular, colonial, and filamentous cyanobacteria, chrysomonads, cryptomonads, diatoms, dinoflagellates, and green algae. Consumers include amoebae, ciliates, flagellates, and a variety of bacteria.

The uppermost 1 mm to 2 mm yellow to orange layer of the benthic communities on most floor areas, composed of organisms largely similar to the plankton, includes bacteria, unicellular and filamentous cyanobacteria, ciliates, diatoms, and dinoflagellates. The second 5 mm to 10 mm green layer contains unicellular and filamentous cyanobacteria, ciliates, filamentous bacteria, and nematodes. A 1 mm to 2 mm red layer of purple bacteria constitutes the third layer. The lowermost layer, of variable thickness (10 mm to 20 mm), is largely living and dead bacteria, moribund cyanobacteria, and black organic muds. All layers contribute to nutrient sequestration (Davis and Giordano 1996), and undergo only slight to moderate accretion.

In the planktonic community of the second half of the salinity range, declining species and levels of diatoms and dinoflagellates are replaced by increasing concentrations of cyanobacteria. Also in ponds of the second half of the salinity range, most fish disappear, fly larvae increase, and a large, self-recruiting *Artemia* population develops. The brine shrimp ingest suspended gypsum crystals (Magaña et al. 2005), and efficiently utilize much of the plankton (Gibor 1957) and other organic substances they consume. The animals deposit their wastes in membrane-bound fecal pellets (Davis and Giordano 1996) that fall to the floor and become incorporated into the benthic community. These activities clear the water (Jones et al. 1981), aid maintenance of the mat, prevent recycle of nutrients, control planktonic *Aphanothece halophytica* and *Dunaliella salina* populations, and assist delivery of high quality, nutrient-depleted brine to the downstream ponds.

Composition, structure, and function of the stratified mats are similar to benthic communities in the first half of the salinity range. As salinity increases, gypsum deposition begins as thin, discontinuous crusts and individual crystals of calcium sulfate interspersed in the uppermost layer of the benthic communities and proceeds to develop firm sheets above the layered mats as salinity increases. Due to the amount of dissolved organic substances in the brine which increase the solubility of certain substances, deposition of calcium carbonate and calcium sulfate (gypsum) may take place at salinities higher than expected.

2.3 High Salinity Communities: 210 PPT to 315 PPT (18^o to 25^o BÉ)

Nutrients from upstream are the chief source of power for these communities whose microorganisms consume more than they produce by photosynthesis. The plankton, algae, bacteria, bacteria-sized cyanobacteria, ciliates, flagellates, and fly larvae may impart a light brown color to the brine. As the resident *Artemia* approach 280 ppt (23^o Bé), most of the population dwindles, becomes moribund, and disintegrates. Also as salinity increases, the aerobic (oxygen requiring) red halophilic bacteria (Halobacteriaceae of the Archaea) colored by red pigments) appear, impart light pink color to the brine and feed on dissolved organic substances. Brine nearly saturated with sodium chloride (320 ppt; Bé 25) flows into deep storage ponds (~1.5 m) which provide a constant supply for crystallizers, and allows area and time for further gypsum deposition.

On the pond floors, the uppermost crystals of the firm and continuous gypsum deposits expose sharp, clear facets to the water, and remain free of mucilage accumulations. Below the gypsum a benthic community of unicellular and filamentous cyanobacteria, and bacteria thrives and forms a 5-cm to 15-cm black organic layer. The community controls leakage and infiltration, slows accumulation of the calcium sulfate (Geisler 1981), and sequesters nurients.

2.4 Crystallizer Ponds: 320 PPT to 355 PPT (25.5^o to 29^o BÉ)

The 30 cm- to 50 cm-deep crystallizers occupy about one-tenth of the total surface area of the saltworks; their communities are sustained by inorganic and organic imports from upstream. Saturated brine from storage, free of microscopic gypsum crystals, first feeds ponds of the parallel series of 2 to 3 connected crystallizers. The small amount of dissolved calcium sulfate remaining in the brine is largely deposited with the sodium chloride in the first crystallizer of each series. The plankton, mostly several genera of aerobic red halophilic bacteria (Oren 2000, 2002 a, 2002 b) feed on dissolved organic substances, reproduce to exceed 10^8 cells ml^{-1}, and color the brine pink to bright red. By consuming significant quantities of organic substances, and by absorbing heat energy from the sun, high concentrations of the red halophilic bacteria decrease organic substances in the brine, improve evaporation, increase the quality of the salt, and improve crystal characteristics (Davis and Giordano 1996). Other plankton, present in low concentrations, include *Dunaliella salina*, amoebae, and flagellates. The salt deposit (the crop) remains firm and well able to support heavy machinery, require scarification before harvest is possible. Below the firm salt floor, filamentous cyanobacteria, bacteria, and black organic materials form a thin community on the native soil. After bittern drainage, the crop is harvested, and washed, and stockpiled without delay; costs of harvest and transport to the wash plant, and losses from the wash process remain unchanging from the outset of the saltworks. Characteristics of freshly harvested salt samples ready for the wash process include high percentages of solid, single, transparent crystals free of colored inclusions, whose longest dimensions are greater than 2 cm, and low percentages of layered “hoppers” (pyramidal and hollow), conglomerate crystals, and small crystals. Large, solid, single crystals are more valuable, bind fewer impurities than other shapes of salt, and enable efficient removal of contaminants with locally designed wash plants, or by commercially available units. Losses of salt in the wash process range from 10% to 12%. Washed salt requires only short residence on the stockpile; typical assays for water and contaminants in salt ready for market are H_20 = 2.5% to 3.0%, Ca^{2+} = 0.03%, Mg^{2+} = 0.02% and SO_4^{2-} = 0.11%.

3. BIOLOGICAL MANAGEMENT AT NEW AND EXISTING SOLAR SALTWORKS

The few and exceptional solar saltworks similar to the above example develop and maintain biological systems favorable to salt production and meet their goals without external biological management. At almost all other saltfields, in-depth knowledge of physical phenomena, recognition of symptoms that indicate onset of problems, implementation of corrective measures, and continuous application of biological management procedures are necessary to attain these goals (Davis 1993, 2000). In new saltworks, management can be facilitated most economically at the planning stage of the saltfield with design compatible to the location, by incorporating features that facilitate computerized control of the salina, and by providing appropriate preliminary information to enable optimal development and management of the physical and biological systems. In existing saltfields whose pond volumes and surface areas are decreasing, in salinas producing salt of diminishing quantity and quality, and in the saltworks requiring expensive losses to prepare their product for market, required control features and pond alterations can be retrofitted into the system, and biological management techniques implemented.

4. IMPORTANCE, ESTABLISHMENT, AND MAINTENANCE OF DESIRED BIOLOGICAL SYSTEMS

A variety of well represented organisms whose species composition and concentrations remain unchanging at each salinity range, distributed over sufficient area, and allowed to develop, enables competition among species for resources, development and maintenance of mats able to efficiently and permanently sequester nutrients, control of leakage and water infiltration, and prevention of undesirable organisms from gaining ascendancy.

With nutrient-poor intake water judicious applications of fertilizers to the ponds can aid establishment of planktonic and benthic communities (Davis 1978). Thereafter, small amounts of fertilizer may be needed only at the intake. However, the nutrient content of the intake usually ranges from sufficient to excessive for establishing a desired biological system.

A steady state system where the salinity at each point in the ponds remains unchanging is essential to successful saltfield operation, and required to establish and maintain desired biological systems. Steady state systems require sufficient numbers of ponds at each salinity range, gates and pumps to regulate salinity, depths and rates of flow, and strategically placed baffles inside ponds to stop back-mixing, eliminate excessive wave fetch, and prevent stagnant brine areas. Also required are reserve capacity at pump stations, and canal or decanting systems situated to quickly drain ponds. Computerized programs can be locally developed or purchased to analyze and integrate routinely gathered information to aid maintenance of steady state systems. This information also serves to determine the status of the biological system, and to identify, and correct developing problems before disasters occur.

5. CAUSES, CONSEQUENCES, AND CURES FOR SLOWLY DEVELOPING DISTURBANCES

Causes of slowly developing disturbances include 1) entry of excessive quantities of nutrients (inorganic, organic, microorganisms) to the salina at the intake, from land runoff, and from large flocks of birds in the ponds, 2) severe wave action in ponds that prevent development of benthic communities, 3) insufficient nutrient sequestering areas in the ponds, 4) brine leakage through dikes, floors, and back-mixing, 5) operation of individual ponds at excessively wide salinity ranges, 6) mixing nutrient-rich subterranean brines with nutrient-rich seawater, 7) enlargement of surface areas of deep ponds without benthic communities, and 8) change in management practices.

Consequences of slowly developing disturbances may require several years to become evident. Their slow appearance often goes unheeded until severe effects attract attention. The effects include decreases of pond surface areas and volumes by fast accreting black substances on pond floors, pond surfaces covered with filamentous algae, and floating mucilaginous rafts, viscous brine and mushy salt in crystallizers, and increasing costs in the harvest and wash processes to attain quality salt. Four problematic organisms, which frequently become apparent and dominant due to the above-mentioned causes and consequences, have been associated with slowly developing disturbances and prolongation of their effects. The algae include *Cladophora*, *Lamprothamnium* and *Ochromonas* at the low salinity range, *Dunaliella salina* at high salinities, and the cyanobacteria *Aphanothece halophytica* at the intermediate salinities.

Cladophora, filamentous green algae, are common at low and intermediate salinity. Filaments grow to become floating mats more than 2 cm to 7 cm thick, cover large surfaces, decrease evaporation, and shade out the benthic community. Large sections that break away float downstream, decay, and release damaging amounts of organic substances.

Ochromonas, microscopic yellow-green planktonic chrysophytes common at low salinity reproduce excessively to dominate the water column, impart yellow-green color to the water, and decrease the effectiveness (nutrient-sequestering ability) of the benthic community. After reaching the intermediate salinity ponds, disintegration and release of organic substances from *Ochromonas* have been associated with *Artemia* populations of reduced size and effectiveness, creation of conditions favorable to the downstream mucilage producing *Aphanothece halophytica* population, excessive gypsum retention in harvested salt, and excessive accretion of black deposits on pond floors.

Lamprothamnium, attached, tree-like green algae 7- to 15-cm tall are common at low salinity. From their first appearance through the time *Lamprothamnium* populations are aggressively spreading, the organisms are well able to sequester nutrients, especially combined nitrogen (ammonium and nitrate) and phosphate. However, after thickly covering the floor of a pond, the *Lamprothamnium* population no longer performs as a nutrient sink but shades out and decreases the effectiveness of the layered benthic community, and allows nutrient-rich water to flow downstream. The *Lamprothamnium* becomes encrusted with mucilaginous algae and cyanobacteria, which break away and float downstream. Upon reaching intermediate salinity, the mineral-rich water, as well as the released microorganisms and mucilage provide levels of nutrients highly favorable to the downstream *Aphanothece halophytica* population.

Aphanothece halophytica, unicellular cyanobacteria common in every salina, develop planktonic monocultures at intermediate salinity, release into the water massive quantities of mucilage, which result in viscous brine that excludes or decimates the *Artemia* population. The layered benthic community, changes from a diverse group of organisms to one dominated by *Aphanothece halophytica,* releases mucilage into the water, and becomes ineffective in nutrient sequestration. Upon reaching the high salinity ponds, viscous substances interfere with gypsum deposition and decrease evaporation. Gypsum deposition occurs not only as firm to soft sheets on pond floors, but also as powdery layers of individual microscopic crystals which are carried downstream (Burnard and Tyler 1993, Magaña et al. 2005). Upon reaching crystallizers, nutrient-rich viscous brine is detrimental to salt quantity and quality, and promotes development of large populations of *Dunaliella salina* which are associated with the adverse effects discussed below.

Dunaliella salina, unicellular algae that reproduce fastest at intermediate salinities, continue to divide slowly after they flow downstream to the high salinity ponds and crystallizers. The algae develop massive populations, release significant quantities of organic substances (Giordano et al. 1993) and color the brine yellow-orange to bright orange. When organic matter from *Dunaliella salina* is supplemented with mucilage produced by *Aphanothece halophytica*, evaporation decreases, and brines become viscous to the touch with high levels of organic substances. In crystallizers, effects of high viscosity include decreased effectiveness of the red halophilic bacteria, crops or salt floors unable to support machinery, and harvests of small and hollow crystals that bind or retain dissolved and crystalline contaminants (Davis and Giordano 1996, Magaña et al. 2005, von Borstal et al. 2000). When allowed to continue, the above events are accompanied by black brine and mushy salt in crystallizers, and necessitate excessive losses of salt in the wash process, prolonged residence of salt on the stockpile, and expensive drying procedures to obtain required purity for market.

Cures at the low salinity range for slowly developing disturbances include use of shallow depths to aid development of nutrient sequestering mats, construction of additional ponds within the circuit to allow narrow salinity ranges in ponds, and to increase the area available for mat development and function, and installation of strategically placed baffles to moderate wave fetch. At intermediate salinities cures include implementation of the above remedies, followed by introduction of functioning *Artemia* populations. In high salinity ponds, floors can be prepared to permit periodic removal of accumulations of gypsum, sediments, and organic substances. In high salinity crystallizers, after the upstream measures are implemented, removal of accumulated mucilage, damaged crops and salt floors allow subsequent deposition of high quality salt.

6. CAUSES, CONSEQUENCES AND CURES OF FAST-APPEARING DISTURBANCES

These disturbances occur after specific events, e.g., failures of pumps, gates and dikes, damage from floods, cyclones and hurricanes, and massive spills of petroleum products. Consequences include fast destruction of the salinity gradient, replacement of desired biological systems by problematic organisms, destruction of the benthic community, and massive releases of organic substances to the brine (Davis and Giordano 1996, Magaña et al. 2005). Other consequences include leakage through damaged dikes and floors resulting in inability to establish a desired salinity gradient, decimation or death of the red halophilic bacteria population, mushy crops and salt floors in crystallizers, increased expenses for salt harvest and hauling, and washing, and decreased quality and quantity of harvested salt.

Cures for fast-appearing disturbances in concentrating ponds include repair of any physical damage, installation of standby pumps at each pump station, armoring vulnerable areas of dikes with rip-rap, and construction of decanters and gates to remove fresh water or mucilage-laden brine. Subsequent measures include restoration of the salinity gradient, use of fertilizers to reestablish benthic communities and seal ponds against leakage (Davis 1978), selection of pond depths to favor development of benthic communities, and reintroduction of functioning *Artemia* populations (Magaña et al. 2005). Effective cures in crystallizers include removal and replacement of brine, crops, and salt floors contaminated by mucilage or petroleum products, and use of caustic soda (Burnard and Tyler 1993) to control the effects of *Dunaliella salina* and decrease contaminants on salt crystals.

REFERENCES

1. von Borstal, L.E., Zimmermann, H. and Ruppert, H. (2000) 'Fluid inclusion studies' in modern halite from the Inagua solar saltwork. *8th World Salt Symposium*, Vol. 2: 673-678.
2. Brown, A. (2000) 'An overview of the world salt industry', *8th World Salt Symposium*, 2:1283-1284.
3. Burnard, E. and Tyler, J. P. (1993) 'Brine quality management in solar salt operations', *Seventh Symposium on Salt* 1:503-508.

4. Davis, J. S. (1978) 'Biological communities of a nutrient enriched salina', *Aquatic Botany* 4:23-42.
5. Davis, J. S (1993) 'Biological management for problem solving and biological concepts for a new generation of solar saltworks', *Seventh Symposium on Salt* 1:611-616.
6. Davis, J. S (2000) 'Structure, function, and management of the biological system for seasonal solar saltworks', *Global Nest: the International Journal* 2:217-226.
7. Davis, J. S and Giordano, M. (1996) 'Biological and physical events involved in the origin, effects, and control of organic matter in solar saltworks', *International Journal of Salt Lake Research* 4:335-347.
8. Geisler, D. (1981) 'Genèse et evolution des gypses des marais salants de Salin-de-Giraud (Camargue)', *Bulletin de Minéralogie* 104:625-629.
9. Gibor, A. (1957) 'Conversion of phytoplankton to zooplankton', *Nature* 179:1304.
10. Giordano, M., Davis, J.S. and Bowes, G. (1994) 'Organic carbon release by *Dunaliella salina* (Chlorophyta) under different growth conditions of CO_2, nitrogen, and salinity',*Journal of Phycology* 30:249-25.
11. Javor, B. J. (2000) 'Biogeochemical models of solar salterns', *8th World Salt Symposium* 2:877-882.
12. Jones, A.G., Ewing, C.M. and Melvin, M.V.(1981), *Biotechnology of solar saltfields', Hydrobiologia* 82:391-406.
13. Magaña, G.Y.G, Lopez, J.C.P, Ortiz, S.M.M., Roche, E.D. and Davis, J.S. (2005) 'Recovery of a commercial solar saltworks damaged by a hurricane; role of biological management', *Proceedings 9th International Conference on Environmental Science and Technology*., A:903-912.
14. Oren, A. (200). 'Salts and Brines', **In** *The Ecology of Cyanobacteria*. Whitton, B.A. and Potts, M. (Eds.) Kluwer Academic Publishers, Dordrecht, 281-306.
15. Oren, A. (2002a) 'Solar Salterns', **In** *Halophilic Microorganisms and their Environments*. Kluwer Academic Publishers, Dordrecht, 441-469.
16. Oren, A. 002b) 'Diversity of halophilic microorganisms: phylogeny, physiology, and applications', *Journal of Industrial Microbiology and Biotechnology* 28:56-63.