HIGH LEVELS OF NUTRIENTS IN THE INTAKE WATER: THE MODERN NEMESIS OF SOLAR SALT MANUFACTURE

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ABSTRACT

High levels of nutrients in a solar saltwork's intake (from seawater, lagoons, lakes, subterranean locations or combinations of these sources) coupled with inability to control the resulting accumulations and consequences of organic substances produced by microorganisms in the concentrating ponds and crystallizers are currently the chief causes of decreased quality and quantity of salt, and increased costs for salt manufacture. Outdated traditional methods employed for design, construction and management of these problematic solar saltworks (salinas, saltfields), appropriate for a time with low concentrations of nutrients in the intake are unable to cope effectively with modern ecological and demographic conditions.

In concentrating ponds of a salina, consequences of high nutrient levels include fast accretion of organic substances in peripheries, floors, and corners that decrease surface areas and volumes, maintain low diversity of microorganisms dominated by organic-producing species (e.g., *Aphanothece halophytica*), stop development of nutrient-removing microorganisms suspended in the water (e.g., *Artemia*) and on pond floors (by layered mats), and prevent delivery of nutrient-poor brine to the crystallizers.

In crystallizers, consequences from high levels of nutrients and organic substances imported from upstream ponds include crops and salt floors with decreased ability to support harvest machinery, release of new organic substances to the brine by the unicellular microorganism *Dunaliella salina*, decreased evaporation and diminished removal of organic substances due to inadequate populations of red halophilic bacteria (*Halobacterium*). Organic accumulations also result in harvest mainly of small, layered hopper crystals and fines that retain liquids and contaminants, increase costs for harvest, salt hauling, and causes large losses in the salt wash process, stacking and recovery operations.

Effective methods reviewed to enable salt manufacture under high levels of nutrients in the intake include ability to change the biological system from plankton to benthic dominated, use of an artificial wetland system to remove important quantities of nutrients from the intake, suppression of nuisance birds, intervention by *Artemia* to significantly decrease levels of *Aphanothece halophytica*, removal of floating algae and accumulations of sediments by mechanical methods, and management and control of the biological system to maximize biodiversity.

Keywords: *Aphanothece halophytica*, biological management, cyanobacteria, *Dunaliella salina*, nutrient-rich intake, solar saltworks.

INTRODUCTION

This report, intended for the salt producer, is based on the author's worldwide field experiences while providing aid to more than 50 seasonal and continuously operated solar saltworks with intakes from seawater, lake water, subterranean brines or combinations of these sources, reviews 1) selected characteristics of solar saltworks commonly encountered, and 2) offers methods for nutrient removal from salinas with high levels of these substances in the intake.

One third of the worldwide manufacture of salt (sodium chloride) comes from solar saltworks (salinas, saltfields) by evaporation of seawater or brines from lakes or subterranean sources. A solar saltworks is a series of connected concentrating ponds through which the intake seawater (or brines) flows downstream, evaporates by wind and sun, gradually increases in salinity, and deposits salt in crystallizing ponds (crystallizers). In each pond of the circuit nutrient-requiring microorganisms (algae, cyanobacteria, protozoa, bacteria, etc.) and macroorganisms (crustaceans, fish, insects, mollusks, sea grasses, seaweeds, etc.) inevitably develop biological systems able to help or harm salt manufacture. Unfortunately today's salinas are threatened by high nutrient levels (ammonium, nitrate, phosphate, and organic substances, e.g., microorganisms and particulates) in the intake that cause development of biological systems detrimental to salt manufacture. High levels of nutrients in the intake seawater (or brines) may originate from effluents of nearby sewage treatment facilities, wastes of mining activities, and reverse osmosis installations, as well as from agricultural runoff, mangrove forests, ocean upwellings, and river mouths.

The threat to existing and new salinas from modern high levels of nutrients is intensified by less than optimal management of depths, flows and salinity gradients, by dated pond design and construction practices (too few ponds, incorporation of deep lagoons or deep areas within the circuit, and lack of sufficient baffles, pumps, gates, weirs, structures to create and control biological systems favorable to salt manufacture). The resulting undesirable biological conditions, e.g., fast accretion of organic deposits in ponds, low biodiversity, destruction of nutrient-removing microorganisms, dominance of problematic microorganisms and their effects on salt manufacture--have become important causes that often prevent realization of the goal of every saltfield—continuous and economic manufacture of high quality salt at design capacity (Davis and Giordano, 1996).

SELECTED CHARACTERISTICS OF A SOLAR SALTWORKS WITH SEAWATER INTAKE AND BIOLOGICAL SYSTEM WHOSE DESIGN AND MANAGEMENT AID SALT MANUFACTURE

The numbers of ponds constructed and utilized at each salinity range[1] enable small salinity increases and maximum numbers of important species in each pond. The salina maintains a carefully controlled salinity gradient, water depth, and flow throughout the circuit to favor plankton or benthic communities, and an unchanging salinity at each point in each pond with baffles, pumps, gates, and weirs. Management also includes twice weekly surveillance of the dikes, collection of salinity, depth and flow rate data, and anecdotal information which is processed in a computer program, and displayed. This salina continuously and economically produces high quality salt at design capacity.

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[1] For convenience, the circuit of ponds is divided into low salinity (Be 3.5 to Be 10), intermediate salinity (Be 10 to Be 20), and high salinity (Be 20 to Be 29) ranges.

Levels of inorganic nutrients and organic substances in the intake are sufficient to 1) create and maintain throughout the entire salina circuit communities of plankton microorganisms suspended in the water and benthic microorganisms on the floor, each community with a stable variety of well represented species and individuals able to thrive at each salinity range.

In ponds of low salinity, plankton communities of producer microorganisms--photosynthetic algae and cyanobacteria (require light and nutrients), and consumer microorganisms (require organic substances)--bacteria, crustaceans, protozoa, etc.—1) aid evaporation, 2) remove nutrients from the water, 3) export to the downstream ponds nutrients sufficient to power the higher salinity biological systems. Benthic communities of algae, bacteria, crustaceans, cyanobacteria, and sediments whose layered structure stays on the floor, maintains desired thickness, controls seepage, and aids nutrient sequestration (removal of nutrients from the overlying water to the sediments of the benthic community).

In the ponds of intermediate salinity imported nutrients power production of new plankton communities dominated by a variety of consumer microorganisms (bacteria, ciliates, flagellates) and low levels of producer microorganisms (diatoms, dinoflagellates, *Dunaliella viridis*, etc.). The consumer plankton includes *Artemia* (brine shrimp), carefully husbanded in selected ponds without fish predation, with depths and flows controlled to maintain large populations of these crustaceans that ingest a variety of suspended microorganisms, organic and inorganic particles. *Artemia* metabolize the ingested organic substances and release wastes in compact fecal pellets which drop to the floor and become food for microorganisms or are locked away in the benthic community. These activities create clear, nutrient-depleted water for export to the downstream high salinity ponds. Benthic communities composed of photosynthetic and consumer organisms develop several layers that maintain desired thickness, control seepage, and sequester nutrients.

In ponds of high salinity, most microorganisms and *Artemia* imported from upstream die and release their contents to form new plankton communities dominated by aerobic red halophilic bacteria (*Halobacterium*) which consume dissolved organic substances and help maintain low levels of *Dunaliella viridis, Dunaliella salina*, and flagellates. Layered benthic communities composed of filamentous and unicellular cyanobacteria, as well as bacteria, ciliates, flagellates, nematodes, and thin black sediments sequester nutrients, maintain thickness, and control seepage. Gypsum is deposited on the floors in firm sheets, whose uppermost crystals have sharp faces without adhering organic substances, and whose lowermost crystals are eroded by bacteria; this process moderates gypsum accumulation.

In crystallizers brine becomes dominated by high concentrations of suspended red halophilic bacteria (*Halobacterium*) which may color the brine red, aid solar energy absorption, increase evaporation and consume important levels of dissolved organic substances. *Dunaliella salina* (orange-colored photosynthetic organic-releasing microalgae) are only occasionally observed. Benthic communities composed of thin layers of photosynthetic cyanobacteria and bacteria below the crops or salt floors, control seepage and maintain thickness. In crystallizers, perimeters of mushy salt are either absent or no more than 5 to 10 cm wide, salt crystals harvested above firm salt or natural floors are mostly large, clear, and single, with low percentages of small hoppers, and fines. Little or no liquid drains from haul vehicles loaded during harvest or enroute to the wash machinery. Losses of salt after a single wash with conventional equipment are 12 to 15 percent; a short residence on the stockpile produces salt ready for market with the assay (in percent) of: Ca = 0.03 to 0.04, Mg 0.02 to 0.03, sulfate 0.11 to 0.12, and insolubles, 0.01 to 0.02.

SELECTED CHARACTERISTICS OF SALINAS WITH NUTRIENT RICH INTAKES AND BIOLOGICAL SYSTEMS NOT FAVORABLE TO SALT MANUFACTURE

A Salina with Seawater Intake

The intake water obtained from a nearby mangrove forest is pumped into a deep lagoon, the first pond of the low salinity range. The suspended community in the lagoon, dominated by high levels of unicellular photosynthetic microalgae (*Ochromonas*), and floating rafts of filamentous green algae (*Cladophora*) that cover large areas of the surface, exports high levels of microorganisms and *Cladophora* fragments to the downstream ponds where they release their nutrients. The lagoon has no benthic community. The remaining low salinity ponds also have suspended communities of few species dominated by *Ochromonas* that color the water green and export high levels of microalgae to the downstream ponds. Benthic communities' thin mats mainly of filamentous and unicellular cyanobacteria above loose, black organic substances are not effective for nutrient sequestration. Accumulated black sediments in pond corners and floors decrease pond volumes and surface areas, and contribute to the exported nutrient load.

In the first half of the intermediate salinity range, plankton communities dominated by high levels of *Ochromonas* prevent sufficient light from reaching pond floors. The sparse *Artemia* population, unable to utilize *Ochromonas*, is too small to effectively remove the microorganisms, organic substances and particulates from the water. In the other half of the salinity range, massive quantities of mucilaginous organic substances produced mainly by large *Aphanothece halophytica* (unicellular, photosynthetic cyanobacteria) populations, living and moribund *Ochromonas*, and nutrients are exported to the downstream ponds. The layered benthic communities of the entire salinity range composed of few species of bacteria, diatoms, cyanobacteria, nematodes, and loose sediments, often separate from the floor and float downstream. The benthic communities, unable to effectively sequester nutrients, facilitate export of nutrients.

In the high salinity ponds, the plankton community dominated by *Aphanothece halophytica* and *Dunaliella salina* populations, suppresses development of red halophilic bacteria, and exports massive quantities of mucilaginous organic substances to the crystallizers.

The benthic community is mainly mucilaginous organic substances and bacteria above and below accumulating gypsum deposited as soft mush, occasional firm sheets, and individual microscopic crystals. Many crystals and significant quantities of dissolved calcium sulfate flow downstream into crystallizers and become incorporated into the salt deposit.

In crystallizer ponds, high levels of nutrients enable growth of large populations of *Dunaliella salina* whose organic release combined with imported organic substances from upstream suppresses development of functional red halophilic bacteria populations. Effects of high levels of organic substances include soft crops and salt floors with decreasing ability to support harvest machinery, and salt crystals mostly small, layered, hollow hoppers and fines that trap contaminants. Perimeters of mushy salt, up to 10 meters wide, pink to red with *Dunaliella salina* and laden with organic substances, are often not harvested, but placed on dikes or redissolved for a future harvest. In the wash process contaminant retention and water content in the harvested salt require high losses, and prolonged residence on the stockpile to reach specifications for market.

SALINAS WITH NUTRIENT-RICH SEAWATER INTAKE SUPPLEMENTED WITH NUTRIENT-RICH SUBTERRANEAN BRINE

Effluents from a nearby population center and agricultural runoff contribute significant quantities of nutrients to the intake seawater. The too few low salinity ponds are fed with seawater intake only, have biological systems with plankton communities of abundant photosynthetic microorganisms of few kinds that color the water green, prevent adequate light from reaching floors, and flow downstream. The sparse consumer microorganisms, mostly ciliates and bacteria, exert little or no control on the producers. Benthic communities—mainly unicellular and filamentous cyanobacteria and bacteria dominated sediments are unable to effectively sequester nutrients.

Nutrient-rich subterranean brine pumped into the first pond of the intermediate salinity range combined with nutrient-rich water from upstream, result in suspended communities dominated by high levels of *Aphanothece halophytica* that prevent light from reaching pond floors, release massive quantities of mucilaginous organic substances and result in viscous water. Sparse populations of consumer microorganisms, unable to control *Aphanothece halophytica* allow most of the organic substances to flow downstream. Benthic communities, also dominated by *Aphanothece halophytica* and loose black sediments, are ineffective for nutrient sequestration, and allow the organic substances to flow downstream. In high salinity ponds, the *Aphanothece halophytica* population decreases, but their organic substances persist, accumulate, and flow downstream. Benthic communities, loose aggregations of filamentous cyanobacteria and bacteria within organic substances above gypsum deposits are ineffective for nutrient sequestration. In crystallizers organic substances from upstream and released from the resident *Dunaliella salina* population, result in viscous brine, soft crops composed mostly of fines, difficulties in salt harvest, high losses in the wash process, and salt manufacture at less than design capacity.

SALINAS WITH CONCETRATED, NUTRIENT-RICH INTAKE FROM INLAND LAKES

The high salinity intake brine contains large quantities of living and dead *Artemia* and their cysts, ciliates, flagellates, and *Dunaliella salina* populations, and high concentrations of organic substances. All ponds are crystallizers whose *Dunaliella salina* populations release organic substances, and whose *Halobacterium* populations color the brine red but are unable to control the accumulating dissolved organic compounds. Salt crystals harvested above organic-laden, soft salt floors are small conglomerates of layered hoppers and fines. Losses in the wash process are high and prolonged residence on the stock pile is needed to bring the crop to market specifications.

SALINAS WITH INTERMEDIATE SALINITY, NUTRIENT-RICH INTAKE FROM SUBTERRANEAN SOURCES

All ponds in the intermediate salinity range have massive populations of organic-releasing *Dunaliella salina*. The ponds have no predators to control the algae population, and no effective benthic communities. In the high salinity ponds also without effective benthic communities, most *Dunaliella salina* die and release their contents, which powers a population of red halophilic bacteria (*Halobacterium*). In crystallizers the large populations of *Halobacterium*, aid evaporation, but are unable to remove significant quantities of organic substances from the brine. The harvested crop, mostly of conglomerated, hollow hoppers, requires high losses in the wash process to reach market specifications.

NUTRIENT REMOVAL METHODS

By an Artificial Wetland
An artificial wetland system was constructed to flow nutrient –rich intake seawater over a shallow area of appropriate dimensions before entering the initial pond of a solar saltworks. The system, designed to remove excessive nutrients from the water contained halophilic grasses, seaweeds and epiphytic microorganisms. Eight months after construction and operation, the system removed 56 percent of the ammonium, 60 percent of the nitrate, and 56 percent of the phosphate from the water (DuToit and Campbell, 2002).

By Bird Control
In small salinas bird scaring devices--noise from cannons and other sources—strategically located and appropriately operated, have significantly decreased deposition of bird droppings in ponds, and predation on *Artemia*. Temporary adjustment of water depths to exclude wading birds has also proven effective (personal experience; also see Cooper et al. 1984, DeGrazio 1989).
By Pond Modifications and Management
Deep lagoons within the pond system allow the energy of sunlight to produce suspended communities only, and export high levels of nutrients to the downstream ponds. Shallow lagoons often develop rooted plants whose surfaces rapidly become covered with organic –releasing microorganisms, many of which detach and float downstream. Lagoons can be excluded from the circuit of ponds, or modified by dividing their shallow peripheries into ponds able to develop controllable plankton and benthic communities.

By Artemia Intervention
Salinas with nutrient-rich intermediate salinity intake water and solar saltworks without effective nutrient sequestering benthic communities have conditions that result in excessive quantities of *Aphanothece halophytica* and attendant consequences detrimental to salt manufacture. Magana et al. (2005) have developed a successful intervention able to remove most of the *Aphanothece halophytica* and suspended particles from a salina. The method involves large scale outdoor cultivation of *Artemia* fed by unicellular green algae (*Dunaliella viridis*) grown under closely controlled conditions of light and temperature. During the evaporation season large numbers of mature *Artemia* are inoculated daily in selected ponds with appropriate salinity, where fish predation is absent, and concentrations of *Aphanothece halophytica* are high.

By Mechanical Means
Rafts of living and moribund *Cladophora*, mucilaginous organic accumulations, and excessive quantities of black organic substances on pond floors and corners are important nutrient sources and can be removed on a routine schedule with mechanical equipment or human labor, and transported to locations where their decomposing substances will not re-enter the pond system. Old salt floors in crystallizers can be harvested and replaced on a routine schedule to remove accumulated organic substances that adversely affect the harvest process, crystal size, and contaminant and water retention of the salt.

By Optimization and Control of the Biological System
Appropriate control of water depths can transition from plankton to benthic community dominance, and adjust nutrient export to downstream ponds.

Maintenance of unchanging salinity at each point in a pond maximizes biodiversity, prevents dominance of undesirable species, and allows a variety of microorganisms to compete for nutrients. Sufficient numbers of ponds at each salinity range that result in small salinity increases in each pond allow creation of efficient nutrient sequestration by benthic communities, and decrease deleterious effects of backmixing. Standby high capacity pumps at each pump station, adjustable gates, frequent surveillance of dikes, and twice-weekly gathered salinity, depth, and flow data also enable optimization of the biological system.

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