Ten commandments for biological management of solar saltworks

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Ten rules for obtaining and maintaining desired biological systems (i.e., those that permit economical and continuous production of high quality salt at design capacity) are presented. Characteristics of desirable and undesirable systems, and functions of key organisms are reviewed. Desired biological systems require proper management of brine salinities, flows, and depths, appropriate management of communities, and special attention to key organisms. Causes of undesirable systems are discussed, and methods to change them to desirable systems are offered.

Physical systems of solar saltworks are generally well understood and properly managed. Saltworks officials use pumps, gates, weirs, and information on salinity, evaporation and flow rates to move brine through their ponds and deposit salt. However, a less understood system that develops in every saltworks—the biological system—can aid or harm salt manufacture. Biologial systems favorable to salt production may develop naturally in well designed, appropriately managed saltworks situated at fortuitous locations. For all other saltworks the biological system must be understood, properly managed, and harmonized with the physical systems to obtain economical and sustained production of high quality salt at design capacity.

This paper summarizes information for officials to manage biological systems of solar saltworks with seawater intake. Salinities are expressed in degrees Baumé (Be); Be=145-145/specific gravity. Ponds containing water from Be 3.5 to Be 25 are termed concentrating ponds; those with brine from Be 25 to Be 29 are crystallizing ponds.

1. KNOW THE STRUCTURE AND COMPOSITION OF YOUR BIOLOGICAL SYSTEM

The biological system in the ponds of every solar saltworks includes communities of organisms (species) in ponds of low salinity (Be 3.5 to Be 5, and Be 5 to Be 10), intermediate salinity (Be 10 to Be 20), and high salinity (Be 20 to Be 29). From the intake to the outflow of most ponds, the salinity of the water increases and a succession of organisms occurs. At each salinity range the biological system has planktonic communities of organisms suspended in the water and benthic communities of organisms living on pond floors. Both communities require light and inorganic and organic substances for their development and maintenance. Organisms favorable and detrimental to salt production live in each community; appropriate biological management maintains high concentrations of organisms favorable to salt production and minimizes numbers of organisms detrimental to salt production.

2. KNOW THE CHARACTERISTICS OF BIOLOGICAL SYSTEMS FAVORABLE TO SALT PRODUCTION (DESIRED SYSTEMS)

Desired systems establish and continuously maintain large numbers of well represented planktonic and benthic species adapted to narrow salinity ranges. Communities in the low salinity ponds manufacture more organic matter than they require for development and maintenance; part of the excess substance flows downstream to develop and maintain desired biological systems in the more saline ponds. Communities in the intermediate salinity ponds exist primarily on organic substances imported from the upstream; however, some new organic matter is produced by algae in these ponds. Communities in high salinity ponds are almost entirely dependent on nutrients flowing in from upstream.

2.1. Low salinity ponds (Be 3.5 to Be 5)

The planktonic community (algae, bacteria, multicellular animals, protozoa) aids solar energy absorption, improves evaporation, and maintains varieties and concentrations of species unchanged over time. Pond floors have patches of seaweeds, filamentous green algae, seagrasses, and scattered marine animals (crustaceans, fish, molluscs, ostracods) above layered mats of microorganisms (benthic communities). The uppermost layer of the benthic communities consists of microorganisms similar to the plankton, the lowermost of bacteria, algae, organic matter, worms, and sediments. The benthic communities remain firmly attached to pond floors, maintain desired species composition, concentrations and thickness over time, prevent leakage, and trap nutrients.

2.2. Low salinity ponds (Be 5 to Be 10)

Composition, function, and characteristics of planktonic and layered benthic communities are similar to those described above; however, in the most saline ponds of the range, seaweeds, most seagrasses, and fish are largely excluded. When plankton flows into the intermediate salinity ponds, most organisms suspended in the water die, and the released nutrients are reused by organisms of the higher salinities to develop desired systems.

2.3. Intermediate salinity ponds (Be 10 to Be 20)

Plankton originating in these ponds includes algae (*Aphanothece halophytica*, *Dactylococcopsis,* diatoms, dinoflagellates, *Dunaliella salina, Dunaliella viridis*, *Synechococcus*), bacteria, brine shrimp (*Artemia*), ciliates (e.g., *Fabrea salina),* and flagellates. Plankton colors the water, aids evaporation, and provides food for brine shrimp. Except for the undesirable *Aphanothece halophytica* (unicellular blue-green algae) and *Fabrea* which are present only in low concentrations, the other organisms remain well represented over time. When ingested by large populations [1-3] of *Artemia*, most planktonic microorganisms and organic substance originating in the intermediate salinity ponds and those imported from upstream are used by the brine shrimp for reproduction, swimming, and life processes. *Artemia* releases its wastes in compact fecal pellets [4] which drop to the bottom of the ponds, where the pellets become incorporated into the benthic community. By these activities, brine shrimp oxidize much of the plankton and particles of organic substances to carbon dioxide and water, partially clarify the brine, allow light to reach pond floors where the benthic community removes significant quantities of nutrients, and prevent *Aphanothece halophytica* and *Fabrea* from reaching damaging concentrations. *Artemia* and microplankton that flow into the most saline high salinity ponds die, and the released nutrients power the new biota (mainly halobacteria) at desired levels.

In most of the intermediate salinity range, benthic communities (layered mats of blue-green algae, bacteria, diatoms, and dinoflagellates, and protozoa) develop, remain firmly attached to pond floors, maintain desired thickness, species composition and concentrations over time, sequester nutrients from the overlying water, and trap oxygen. In the highly saline ponds of the range, blue-green algae and bacteria live within and below firm deposits of gypsum on pond floors.

2.4. High salinity ponds (Be 20 to Be 29)

Plankton produced in these ponds consists primarily of high concentrations of red halophilic bacteria (species of aerobic *Halobacterium* and *Halococcus*) and low concentrations of *Dunaliella salina*. The bacteria oxidize (consume) most organisms, as well as dissolved and particulate organic substances imported from the intermediate salinity ponds, and then they multiply to color the brine and aid solar energy absorption.

Benthic communities consist of filamentous blue-green algae, bacteria, and organic substances within and under firm deposits of gypsum (Be 20 to Be 25), and under firm layers of salt (Be 25 to Be 29). In addition to functions previously described, these communities also prevent excessive accumulations of gypsum. In crystallizer ponds, characteristics of salt crystals remain desirable, contaminant concentrations in salt remain low over time, and the crop (harvestible salt) and floors of soil or salt remain firm and able to support heavy equipment over time. (A sample of salt with desirable crystal characteristics and low contaminants has a high percentage of solid and large transparent crystals, low percentage of hopper-shaped, hollow, small, and opaque crystals, and low assays of contaminants, e.g., calcium 0.03-0.05%, magnesium 0.02-0.04%, sulfate 0.11-0.16%, and insolubles 0.01-0.02%).

3. KNOW HOW TO KEEP THE BIOLOGICAL SYSTEM HEALTHY

Narrow and unchanging salinity gradients within each pond and only small salinity differences between ponds allow a large variety of desirable organisms to grow and reproduce, compete for nutrients, and prevent dominance of the few species that produce mucilage, release organic substances, or destroy *Artemia* populations. Biodiversity and narrow salinity gradients are maintained by appropriate numbers of ponds, proper management of brine salinities, flows and depths, strategically situated finger dikes that partially traverse large ponds, reduce effects of waves, and minimize backmixing, standby pumps at every pump station, dikes impervious to water between ponds and on pond perimeters, decanters to remove rainwater from pond surfaces, and by allowing small amounts of salt to precipitate on floors of the highest salinity concentrating ponds. Appropriate water depths maintain desired balance between planktonic and benthic communities, moderate temperatures for *Artemia*, and keep the benthic community in a functioning condition. Because petroleum products are highly damaging to bacteria in high salinity, special efforts to prevent and/or remove spills in crystallizer ponds are essential [5].

Constant surveillance and study of all ponds to determine the status of the biological systems and any changes in the communities are essential. Appropriate data gathering, display, and timely analysis of the information by a specialist of biological management of solar saltworks can detect the onset of problems, allow adjustments, and prevent disasters.

4. KNOW THE ELEMENT REQUIREMENTS OF YOUR SYSTEM—WHERE THEY COME FROM AND WHERE THEY GO

Organisms in solar saltworks require many elements, most of which are available at appropriate concentrations in seawater. However, concentrations of combined nitrogen (as ammonium, nitrate, organic nitrogen) and phosphorus (as inorganic and organic phosphate) may be insufficient or too high for development and maintenance of desired biological systems.

Sources of combined nitrogen and phosphate for solar saltworks include the intake seawater, land runoff, bird droppings, fertilizer supplements, and nitrogen-fixing microorganisms in benthic communities in the low salinity range. Nitrogen fixation converts gas nitrogen from the atmosphere to combined nitrogen.

In desired systems, excessive minerals and organic matter are permanently sequestered in the lowermost layers of benthic communities. Discarded bitterns containing high concentrations of dissolved inorganic and organic substances constitute an important exit of combined nitrogen and phosphate from the saltworks [6].

5. KNOW THE FUNCTIONS OF THE KEY ORGANISMS

Key organisms include species favorable to salt production (*Artemia, Dactylococcopsis, Dunaliella viridis,* aerobic *Halobacterium* and *Halococcus, Synechococcus*) and species detrimental to salt production (*Aphanothece halophytica, Dunaliella salina, Fabrea salina*). Species remain favorable or detrimental only when their concentrations are high.

5.1. *Aphanothece halophytica*

These unicellular blue-green algae reproduce and grow best in the intermediate salinity range, they remain alive in brine almost saturated with sodium chloride, and they are not suitable food for *Artemia.* In desired biological systems the algae may be almost absent from the plankton, but on pond floors *Aphanothece* populations contribute to the sealing qualities of a diverse benthic community. Fluctuating salinities, excessive nutrients, and other disturbances that exclude competing organisms allow *Aphanothece* to reproduce at fast rates and release mucilage that accumulates in the water and on pond floors above benthic communities. In crystallizer ponds *Aphanothece* cells die, but their cell walls and mucilage persist for long periods of time.

5.2. *Artemia*

Due to their activities in the intermediate salinity ponds, brine shrimp are an essential link between the massive imports from the large upstream ponds and the much smaller biota of high salinity ponds [7-9]. The link requires large *Artemia* populations with voracious appetites, and ability to grow, reproduce and quickly reestablish functioning populations after cold seasons. *Artemia* populations that lack one or more of these characteristics can be replaced with strains of the animals more suitable to salt production.

5.3. *Dactylococcopsis* and *Synechococcus*

These non mucilage-producing blue-green algae characteristic of the plankton of most salinas in the Western Hemisphere [9] grow and reproduce in salinities of Be 16-23. In desired biological systems, large populations develop, color the water brown, and aid evaporation. In crystallizer ponds, the aerobic halobacteria are able to utilize both *Dactylococcopsis* (*Myxobactron*), and *Synechococcus*.

5.4. *Dunaliella salina* and *Dunaliella viridis*

Both species are planktonic, suitable as food for *Artemia,* and reproduce and grow best in the intermediate salinity ponds. Although *Dunaliella viridis* is rarely found at salinities above Be 25, *Dunaliella salina* survives and reproduces slowly throughout the high salinity range where predation by *Artemia* is minimal or absent. In biological systems favorable to salt production, nutrient removal by competing organisms, by *Artemia* and by benthic communities keep populations of both algae at desired levels. However, when subjected to disturbances (e.g., fluctuating salinities, high nutrient concentrations, inappropriate management of physical systems), large populations of *Dunaliella salina* develop that release damaging quantities of organic substances to the brine of intermediate and high salinity ponds [10].

5.5. *Fabrea salina*

Too large to be consumed by *Artemia*, these planktonic ciliates grow and reproduce in ponds of intermediate salinity. In desired biological systems, only low concentrations of *Fabrea* occur, but under a variety of disturbances, large populations may develop. Because large populations of *Fabrea* consume most of the suspended microorganisms and particulates before they encyst and become dormant, the *Artemia* colony becomes starved and decimated. Until the *Artemia* population becomes reestablished, services normally performed by the brine shrimp are suspended, and massive quantities of organic substances flow into the high salinity ponds.

5.6. *Halobacterium* and *Halococcus*

Aerobic halobacteria (red halophilic bacteria) reproduce and grow best in mucilage-free brines of high salinity ponds containing sufficient suitable food (as *Artemia,* diverse plankton and organic particulates from upstream). Large and healthy populations (often at 10^9 bacteria per liter in crystallizer ponds) color the water pink to red [10-11], aid brine evaporation, and maintain organic substances imported from upstream at desired levels.

6. KNOW THE CHARACTERISTICS OF UNDESIRABLE BIOLOGICAL SYSTEMS

6.1. Inadequately developed systems

These systems, typical of new salinas, are inadequate to color water, seal ponds, and are unable to produce sufficient quantities of organisms. Sparse plankton populations result in clear water, less than expected evaporation, and insufficient organic matter in the ponds for development of desired biological systems [12]. Insufficiently developed benthic communities allow brine leakage through pond floors and dikes, result in loss of ionic control, and they require surface area ratios of concentrating to crystallizer ponds greater than 10:1.

6.2. Excessively developed systems

These accumulate massive quantities of mucilage on pond floors and black organic substances below benthic communities, in pond corners, and along dikes. Mucilage accumulations destroy benthic communities, increase brine viscosity, decrease pond surface areas and volumes. Decreased surface areas and volumes result in decreased evaporation, decreased salt production, and increased sensitivity of the biological system to rainfall. A sample of harvested salt from crystallizer ponds fed with viscous brine consists mainly of small and hopper-shaped crystals whose cavities entrap contaminants similar to the brine mother liquor [13]. The salt deposit (crop) and/or floors (salt or soil) of crystallizer ponds become soft and unable to support heavy equipment [14].

7. KNOW HOW TO CHANGE UNDESIRED BIOLOGICAL SYSTEMS TO DESIRED SYSTEMS

7.1. Inadequately developed systems

Inadequately developed systems are the result of insufficient concentrations of combined nitrogen and phosphate in the intake water. Fertilizer supplements appropriately applied and monitored can establish desired planktonic and benthic communities [12]. After communities attain desired characteristics, small amounts of fertilizers applied at the intake of the saltworks may be required from time to time.

A method suggested by Garrett [15] for seepage reduction involves diversion of intermediate or high salinity brine to ponds that leak water through their floors or dikes. Use of green dyes to increase evaporation of crystallizer brine has proven useful. However, dyes should be discontinued after a time in order to ascertain whether natural color develops from red halophilic bacteria.

7.2. Excessively developed systems

Strategies for decreasing levels of nutrients in the intake water include use of broad, shallow areas through which water flows before it enters the pond system. During a nine-month period, a "constructed wetlands" (du Toit and Campbell, unpublished) removed more than 50 percent of the combined nitrogen and phosphate from the water. Other strategies include relocation of intake pumps to areas of decreased water turbulence or to locations with decreased nutrients [7, 8].

Excessively developed planktonic communities can be controlled by maintaining salinities within ponds in a narrow and unchanging range, keeping water at levels that allow light to reach the pond floors, and by harvesting fish, brine shrimp, and penaeid shrimp. Because bird droppings constitute an important source of excessive nutrients in some saltworks, noise cannons appropriately placed and moved from time to time are useful. Excessively developed benthic communities may be controlled by mechanically removing sediments, flushing of concentrating and crystallizing ponds with seawater, and by periodic removal and replacement of floors (soil or salt) in crystallizer ponds [7, 8]. Redesign of a saltworks is indicated when numbers of ponds are insufficient to establish and maintain desired systems, or when the pond system is inappropriately matched to the coupled systems (see Commandment 9).

8. KNOW HOW DISTURBANCES CHANGE DESIRABLE SYSTEMS TO UNDESIRABLE SYSTEMS

8.1. Inappropriate management of water depths

In order to increase evaporation and quantity of harvested salt, some management officials fill the low salinity ponds well beyond their usual surface areas and volumes. Consequences resulting from the increases in salinities include death of planktonic and benthic organisms adapted to the previous range, massive increases of floating filamentous algae, and separation from pond floors of large segments of benthic communities that dissolve and flow downstream. Because the consequences of inappropriate water depths release excessive nutrients to the intermediate salinity ponds, *Aphanothece halophytica,* and *Dunaliella salina* reproduce massively and suppress the *Artemia* population. Increased salinities also precipitate gypsum above benthic communities; this severely decreases nutrient sequestering and results in excessive flow of organic substances to the downstream ponds. In high salinity ponds, the red halophilic bacteria are able to maintain organic substances imported from upstream at appropriate levels for a time. However, as the organic substances concentrate and oxygen becomes depleted in crystallizer ponds, the red halophilic bacteria population declines, the salt deposit and salt floors of soil or salt become soft, and the quality of the salt decreases. In extreme cases the brine becomes black with organic substances, and the entire salt deposit "mushy" and difficult to harvest.

8.2. Brine dilution (from rainfall, broken dikes, land runoff) and salinity fluctuations

These disturbances change communities of diverse biotas in intermediate salinity ponds to communities dominated by *Aphanothece halophytica, Dunaliella salina,* and *Fabrea salina*. In high salinities, severe brine dilution kills halobacteria [16] and allows large quantities of organic substances to accumulate in crystallizer ponds.

8.3. Excessive nutrients

This disturbance is characterized by continued input of combined nitrogen, phosphate, microorganisms, and organic substances at concentrations greater than required for obtaining and maintaining desired biological systems. Results of excessive nutrients are discussed under Section 6.2.

8.4. Pollutants

Saltworks located near harbors, heavy industry, farm lands, or large human population centers may receive petroleum products, pesticides and other poisons from the intake water as well as heavy metals, undesirable particulates and gases from the atmosphere. Pollutants originating inside the saltworks include petroleum products (oil, fuel, grease, and hydraulic fluids) from pumps, harvest machinery, and salt hauling trucks. Detrimental effects of petroleum products on halobacteria have been noted; effects of other pollutants on the organisms of the aquatic environment are deleterious.

8.5. High velocity winds

Strong winds mix brines of significantly differing salinities (backmixing) within ponds, destroy biodiversity, benthic communities and dikes, and decimate the *Artemia* population [17]. Results of the disturbances cause massive reproduction of organic-releasing organisms, release of nutrients to the water, and curtail nutrient sequestering by benthic communities.

9. KNOW HOW YOUR BIOLOGICAL SYSTEM IS COUPLED TO OTHER SYSTEMS

Other systems (nearby river mouths, industry, tidal flats, mangrove thickets, power-generating facilities, large human and animal populations, tides) may aid or harm salt production. By supplying appropriate concentrations of nutrients and microorganisms, coupled systems may be essential to the proper operation of a saltworks. However, coupled systems may release levels of nutrients, poisons and heavy metals to the intake water and become highly detrimental to salt production. Changes in systems (e.g., demographics) connected to saltworks can convert desired biological systems to undesirable systems.

10. KNOW THE TIME ELAPSED BETWEEN A DISTURBANCE AND ITS CONSEQUENCE

Consequences of high velocity winds, floods and sustained rainfall to broken dikes, benthic communities, and the salinity gradient occur in a relatively short time. However, consequences of suboptimal management of the physical and biological systems, inappropriate saltworks design (not properly matched to coupled systems, insufficient number of ponds), gradual accumulations of pollutants and organic substances in ponds, and nutrient-rich intake water occur slowly and may be tolerated or go unnoticed during the tenure of a management official. Correction of the consequences can be difficult, costly, and time consuming [8].

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