Desalination and Water Treatment
www.deswater.com

1 (2009) 68–74

1944-3994/1944-3986

Salinity tolerance evaluation methodology for desalination plant discharge

Nikolay Voutchkov

Poseidon Resources Corporation, 1055 Washington Boulevard, Stamford, CT 06901, USA
Tel. +1 203 327 7740, ext. 126; Fax: +1 203 327 5563; email: nvoutchkov@poseidon1.com

Received 8 January 2008; Accepted 5 October 2008

ABSTRACT

Seawater desalination plants generate concentrate (brine) which typically has 1.5 to 2 times higher total dissolved solids concentration (salinity) than that of the ambient seawater. When returned to the ocean without dilution, this concentrate may have a negative impact on the aquatic environment in the area of the discharge. The environmental impact of the desalination plant discharge is very site-specific and depends to a great extent on the salinity tolerance of the specific marine organisms inhabiting the water column and benthic environment influenced by the discharge. This work presents methodology that allows establishing the site-specific maximum level of salinity concentration (salinity tolerance threshold) at which marine organisms not only survive, but can also grow and reproduce normally. The described method was used successfully for the permitting of the concentrate ocean discharge of two large seawater desalination projects in California — the 189,000 m^3/d (50 MGD) Carlsbad and Huntington Beach desalination plants.

Keywords: Desalination; Salinity tolerance; Discharge; Concentrate; Seawater, brine

1. Introduction

Environmentally safe disposal of the concentrate produced by seawater desalination plants is one of the key factors determining the viability, size and costs of a given project. The maximum total dissolved solids (TDS) concentration (salinity) that can be tolerated by the marine organisms living in the desalination plant outfall area is defined as a salinity tolerance threshold and depends on the type of the aquatic organisms inhabiting the area of the discharge and the period of time these organisms are exposed to the elevated salinity [1]. These conditions are very site-specific for the area of each desalination discharge and therefore, a general rule of thumb for determining the salinity tolerance threshold is very difficult to develop.

Currently, the methodology commonly used to evaluate the impact of desalination concentrate discharge on marine organisms is the United States Environmental Protection Agency (US EPA)'s whole effluent toxicity (WET) test. This test, however, only allows predicting salinity (TDS) levels above which marine organisms die. Maintaining a healthy marine environment in the area of the desalination plant discharge requires salinity to be maintained at level at which aquatic life is not only alive but also is not exposed to continuous stress and gradual ecosystem deterioration. This environmentally safe salinity tolerance threshold would typically be below the level at which aquatic life mortality occurs.

A new methodology for determination of the salinity tolerance of the aquatic life inhabiting the area of a desalination plant discharge was developed at the Carlsbad seawater desalination demonstration plant in California. The new methodology allows to establish the maximum salinity level at which marine organisms not only survive but also maintain healthy growth and normal reproductive ability under the conditions of long-term exposure to the elevated salinity in the area of the discharge. This methodology includes the following four key steps:

- determination of the discharge salinity range;
- identification of site-specific test species inhabiting the discharge area;

- Biometrics test at average discharge salinity;
- Salinity tolerance test at varying concentrate dilution levels.

2. Determining discharge salinity range

The first step of the salinity tolerance evaluation (STE) methodology is to define the minimum and maximum TDS concentrations that are projected to occur in the area of the discharge after the start up of desalination plant operations. This salinity range should be established taking under consideration the effect of mixing and associated dilution in the area of the discharge as a result of the site-specific natural hydrodynamic forces in the ocean (currents, winds, tidal movements, temperature differences, etc.) as well as the mixing energy introduced with the desalination plant discharge diffuser system (if diffusers are used to dissipate the discharge). If the desalination plant concentrate is diluted by mixing with other lower-salinity discharge (i.e., cooling water from power plant or wastewater treatment plant effluent) prior to its exit from the outfall into the ocean, this additional dilution should also be accounted for when establishing the salinity range for which the salinity tolerance of the aquatic species is assessed.

In general, discharge salinity is expected to decrease with increase of the distance from the point of concentrate discharge and to increase with depth [2]. The rate of decrease of discharge salinity from the point of discharge depends on the hydrodynamic conditions in the vicinity of the discharge. Because of the complexity of the various factors that impact the mixing and dilution of desalination plant concentrate with the ambient ocean water, especially for large projects (i.e. projects with discharge volume of 1 MGD or higher), the actual salinity range that would occur in the area of the discharge should be determined based on hydrodynamic modeling [2,3].

As a minimum, the set of test concentrations is recommended to include the TDS concentration at the middle of the water column and the middle of the zone of initial dilution (ZID) and the maximum seabed salinity concentration at the edge of the ZID [2]. The ZID is defined as the area of the ocean within 330 m (1,000 ft) from the point of the desalination plant discharge. The TDS concentration in the middle of the ZID and the middle of the water column is representative for the average steady-state salinity of the discharge. Most marine organisms (fish, plankton, etc.) swimming or floating through the discharge area would typically be exposed to this salinity level. The maximum seabed salinity at the edge of the ZID is representative for the TDS level that is projected to occur on the ocean bottom and the testing for this salinity allows to account for the impact of the discharge on the benthic marine organisms.

3. Selecting indicative marine organisms

The purpose of the second step of the STE methodology is to identify the most sensitive, site-specific species that would be indicative of the salinity tolerance of the aquatic flora and fauna in the area of the desalination plant discharge. These species are used for the biometrics and salinity tolerance tests. At least three species should be selected for the tests: one representative for the fish population in the area, one for the invertebrate population and one for macro-algal population (i.e., kelp, red alga, etc), if such species are present and occur in significant numbers [4–6]. The selection of the specific test species should be completed by an expert marine biologist that is very familiar with the site-specific aquatic flora and fauna in the area of the desalination plant discharge. The test species should be selected based on: (1) presence and abundance in the area; (2) environmental sensitivity (i.e., endangered/protected marine species are first priority); (3) sensitivity to salinity in the range projected to occur in the discharge; (4) significance in terms of commercial and recreational harvesting/fishing.

4. Biometrics test

The purpose of the biometrics test is to track how well the indicative test species will handle a long-term steady-state exposure to the elevated average discharge salinity that will occur in the middle of the zone of initial dilution after the desalination plant is in operation [7]. The biometrics test should be completed in a large marine aquarium (test tank) in which the desalination plant concentrate is blended with ambient seawater to obtain salinity not to be exceeded in the middle of the ZID in the ocean for at least 95% of the time. This salinity level should be maintained in the aquarium for the duration of the test. In addition, a second aquarium (control tank) of the same size and number and type of test marine organisms should be employed, with the main difference that this tank should be filled up with ambient seawater collected from the area of the discharge. The control tank should be operated in parallel with the test tank and observations from this tank would be used as a base for comparison and statistical analysis.

Once the salinity in the test and control aquariums is set to target levels, all aquariums should be populated with the selected test species. Key biometric parameters (appearance, willingness to feed, activity, weight gain/loss, and gonad production) of these species should be monitored frequently (minimum once every 2 days) by an expert marine biologist over a prolonged period of time (minimum of 3 months, preferably 5 or more months). Percent weight gain/loss and fertilization for one or more of the test and control organisms should be measured as well.

At the end of the test, the qualitative and quantitative biometric parameters of the marine species in the test and control tanks should be compared to identify if the same species exhibit statistically significant differences—especially in terms of weight gain/loss and fertilization capabilities. If such differences are not observed, then the desalination discharge is not likely to trigger alteration of the ambient aquatic environment and the discharge would be environmentally safe. If all species exhibit statistically significant differences, then the discharge design and conditions may need to be modified to prevent significant alteration of the marine environment. If only few species exhibit statistically significant differences, then desalination plant discharge design may or may not need to be modified depending on the type of the affected species. A majority of the mobile marine species that inhabit the water column, such as most fish, have sensors that would allow them to discern the higher salinity environment around the discharge and to swim away from this area. Therefore, if the results from the biometrics test indicate that the only marine organisms being impacted are mobile marine species, then this discharge would be environmentally safe, but may cause alteration of the speciation of marine inhabitants in the area in the immediate vicinity of the discharge.

If the biometrics test results show that the only impacted species are stationary (for example: seagrass, kelp, benthic flora and fauna), then the habitats of these marine organisms are likely to be reduced in size and/or diversity over time as a result of the desalination plant discharge. To address this concern, the desalination plant discharge would need to be either extended beyond the boundaries of the affected habitats or modified to eliminate the possibility for habitat alteration.

5. Salinity tolerance test

The main purpose of the salinity tolerance test is to determine if the marine organisms around the area of the discharge will survive the extreme salinity conditions that may occur over short periods of time within the ZID and on the edge of the ZID. Due to the natural variability of the mixing conditions in the ocean (such as changes in wind speed and direction, tidal levels, direction and velocity of underwater currents, etc.), it is likely that occasionally the discharge salinity may exceed the average steady-state salinity level for which marine species were tested during the biometrics test. The salinity tolerance test would indicate if the marine organisms would be able to retain their capacity to reproduce after exposure to the short-term extreme salinity conditions that are expected to occur in full-scale operations under a worst-case scenario. The test species should be exposed to several blends of concentrate and ambient seawater that can occur within the range of the discharge salinities. The low end of the range should be the average salinity in the ZID (mid-depth) and the high end should be the maximum salinity above the seabed at the boundary of the ZID (i.e., 330 m) from the point of the discharge).

Similar to the biometrics test, this experiment includes two sets of aquariums for each salinity concentration — a series of test tanks, one for each test salinity level, and a control tank. The duration of the salinity tolerance test should be determined by the projected length of occurrence of the worst-case discharge salinity scenario. This duration should be established based on the results from hydrodynamic modeling of the desalination plant discharge for worst case scenario conditions (i.e., low wind velocities, low tides, etc.). Usually, extreme salinity discharge conditions are not expected to continue for more than 2 weeks. However, if this is likely in specific circumstances, then the length of the study should be extended accordingly. Starting from the low end of the salinity concentration, individual test tanks should be set for salinity increments of 1,000 mg/L to several thousand mg/L to cover the range, until the maximum test salinity concentration is reached.

The salinity tolerance test would identify the maximum salinity level at which the marine species indicative for the aquatic flora and fauna of the discharge area can survive extreme conditions that may occur occasionally in the area of the discharge. This salinity threshold would be determined comparing the number of species that have survived various levels of salinity against the survival rate of the test species in the control tank. The highest TDS concentration at which the number of surviving organisms is the same or higher than that in the control tank would be considered the salinity threshold for this specific discharge.

Many marine organisms have natural ability to adapt to a wide range of salinity concentrations as long as these changes occur gradually. For instance, organisms exposed to increasing salinities in series of small increments can tolerate higher salinities than organisms exposed to higher salinities. Since the salinity tolerance test includes direct exposure of the test species to high salinity environment without any incremental acclimation and adaptation, this test would typically yield conservative results and is representative for "worst-case" conditions where the marine species are exposed to abrupt increase in salinity.

6. Application of the STE procedure to the Carlsbad desalination project

The STE procedure described above was applied to assess the discharge impact of the 190,000 m^3/d (50 MGD) Carlsbad seawater desalination project, located in southern California. This project includes a direct

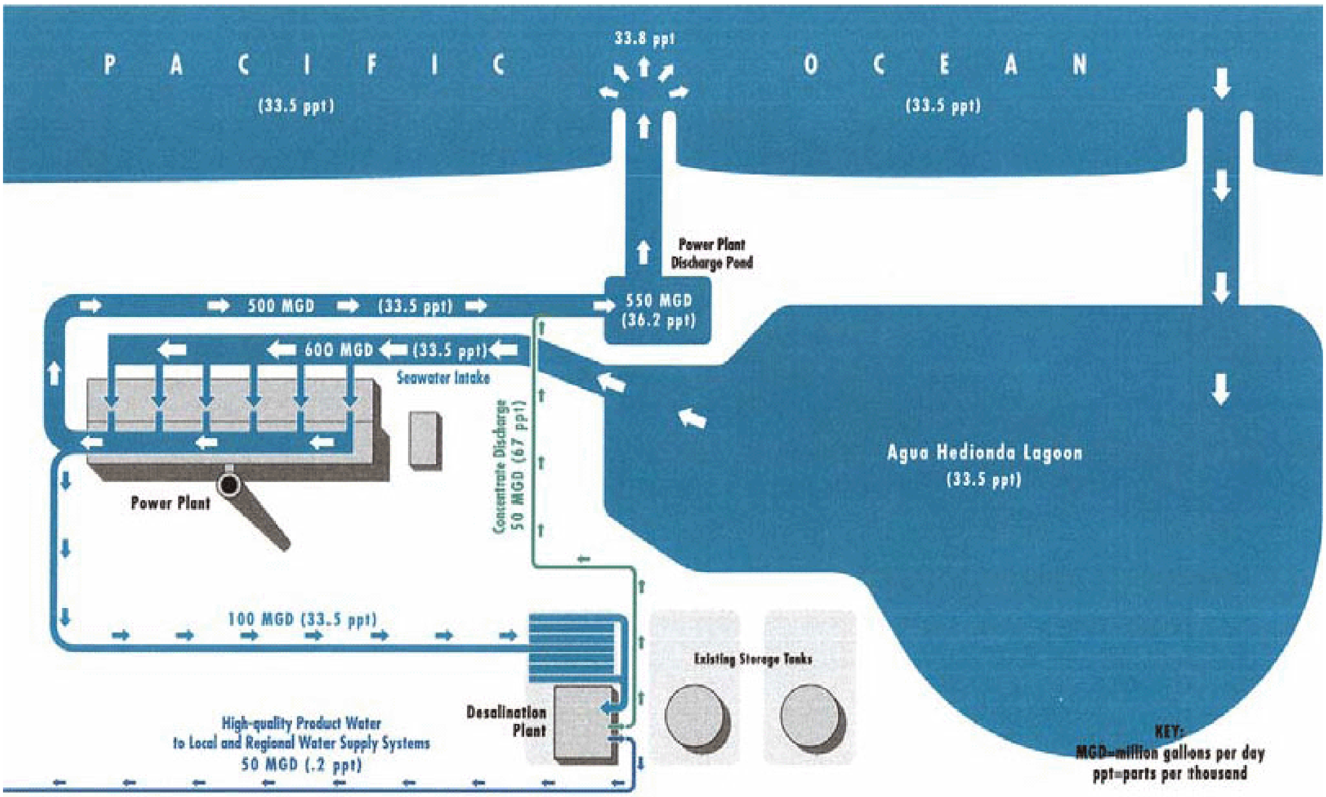

Fig. 1. Collocation of Carlsbad desalination plant with the Encina power station.

connection of the desalination plant intake and discharge facilities to the discharge outfall of an adjacent coastal power generation plant using seawater for once-through cooling (see Fig. 1). The power plant has a total of five power generators and depending on the number of units in operation pumps between 757,000 m^3/d and 3,103,700 m^3/d (200 MGD and 820 MGD) of cooling water through the condensers. The warm cooling water from all condensers is directed to a common discharge tunnel and lagoon leading to the ocean. The full-scale desalination facility is planned to tap into this discharge tunnel for both desalination plant feed water and for discharging high-salinity concentrate downstream of the intake area.

Water collected from one end of the power plant discharge canal will be conveyed to the desalination plant to produce fresh water, and the concentrate from the desalination plant will be returned into the same discharge canal, approximately 250 m (800 ft) downstream from the point of intake. The desalination plant concentrate, containing approximately two times the salinity of the source seawater (68 ppt vs. 33.5 ppt) will be blended with the remaining cooling water discharge of the power plant and conveyed to the ocean for disposal.

The salinity range of the mixed discharge from the Carlsbad seawater desalination plant and the power plant will be between 35 parts per thousand (ppt) to 40 ppt. The average salinity in the middle of the ZID is projected to be 36 ppt. Therefore, the biometrics test was completed for this salinity, while the test range for the salinity tolerance test covered 37 ppt to 40 ppt in 1 ppt increments. Both tests were executed by Dr. Steven Le Page of M-REP Consulting [7], who is very familiar with the local flora and fauna in the area of the future desalination plant discharge.

A list of the 18 marine species selected for the biometrics test for the Carlsbad project is presented in Table 1. The salinity tolerance test was completed using three local species which are known to have the highest susceptibility to stress caused by elevated salinity [7,8]: (1) the purple sea urchin (*Stronglyocentroutus purpuratus*) (Fig. 2); (2) the sand dollar (*Dendraster excentricus*) (Fig. 3); and (3) the red abalone (*Haliotis rufescens*) (Fig. 4).

The biometrics and salinity tolerance tests were completed in 110-gal marine aquariums (Fig. 5). The biometrics test was continued for a period of 5.5 months. The results of this test are summarized in Table 2, and indicate that all organisms remain healthy throughout the test period. No mortality was encountered and all species showed normal activity and feeding behavior. The appearance of the individuals remained good with no changes in coloration or development of marks or lesions.

Fig. 2. Purple sea urchin.

Fig. 3. Sand dollars.

Table 1
Marine species used for the Carlsbad biometrics test

	Scientific name	Common name	Number of individuals per species
1	*Paralichthys californicus*	California halibut	5 juveniles
2	*Paralabrax clathratus*	Kelp bass	3 juveniles
3	*Paralabrax nebulifer*	Barred sand bass	3 juveniles
4	*Hypsoblennius gentilis*	Bay blenny	5
5	*Strongylocentrotus franciscanus*	Red sea urchin	4
6	*Strongylocentrotus purpuratus*	Purple sea urchin	14
7	*Pisaster ochraceus*	Ochre sea star	3
8	*Asterina miniata*	Bat star	3
9	*Parastichopus californicus*	Sea cucumber	2
10	*Cancer productus*	Red rock crab	2
11	*Crassadoma gigantea*	Giant rock scallop	3
12	*Haliotis fulgens*	Green abalone	3
13	*Megathura crenulata*	Giant keyhole limpet	3
14	*Lithopoma undosum*	Wavy turban snail	3
15	*Cypraea spadicea*	Chestnut cowrie	3
16	*Phragmatopoma californica*	Sand castle worm	1 colony
17	*Anthropleura elegantissima*	Aggregating anemone	4
18	*Muricea fruticosa*	Brown gorgonian	1 colony
19	*Haliotis rufescens*	Red abalone	5
20	*Dendraster excentricus*	Sand dollar	5

The duration of the salinity tolerance test for the Carlsbad project was 19 days. The results of this test are given in Table 3 and show that both sand dollars and red abalones had 100% survival in all test tanks and in the control tank. One individual of in the Purple sea urchin group died in each of the test tanks and one died in the control tank. Therefore, the adjusted survival rate for the Purple sea urchins was also 100%. These test results confirm that the marine organisms in the discharge zone would have adequate salinity tolerance to the desalination plant discharge in the entire range of operations of the desalination plant (i.e., up to 40 ppt). All individuals of the three tested species behaved normally during the test, exhibiting active feeding and moving habits.

In summary, the salinity tolerance evaluation methodology applied to the Carlsbad seawater desalination project confirms that the elevated salinity in the vicinity of the plant discharge would not have a measurable impact on the marine organisms in this location and these organisms can tolerate the maximum salinity of 40 ppt that could occur in the discharge area under extreme conditions.

Fig. 4. Red abalone.

Fig. 5. Carlsbad biometrics test tank.

Table 2
Overall condition and average weight gain of biometrics test species

Scientific name	Common name	Avg. % wt. change (g)	% wt. change (control group)	Sig.	Appearance and feeding
Paralichthys californicus	California halibut	91.3	96.9	n/s	Strong
Paralabrax clathratus	Kelp bass	114.3	104.8	n/s	Strong
Paralabrax nebulifer	Barred sand bass	106.8	113.5	n/s	Strong
Hypsoblennius gentilis	Bay blenny	120.0	107.1	n/s	Strong
Strongylocentrotus franciscanus	Red sea urchin	2.8	2.4	n/s	Strong
Strongylocentrotus purpuratus	Purple sea urchin	7.9	7.2	n/s	Strong
Pisaster ochraceus	Ochre sea star	3.8	4.6	n/s	Strong
Asterina miniata	Bat star	2.8	3.1	n/s	Strong
Parastichopus californicus	Sea cucumber	−2.2	2.3	n/s	Strong
Haliotis fulgens	Green abalone	9.6	7.7	n/s	Strong
Megathura crenulata	Giant keyhole limpet	5.1	4.7	n/s	Strong
Lithopoma undosum	Wavy turban snail	3.9	2.4	n/s	Strong
Cypraea spadicea	Chestnut cowrie	0.6	1.0	n/s	Strong
Anthropleura elegantissima	Aggregating anemone	115.9	48.9	n/s	Strong
Haliotis rufescens	Red abalone	9.2	7.8	n/s	Strong
Dendraster excentricus	Sand dollar	3.5	4.5	n/s	Strong

Note: n/s = not significant and Sig. = statistical significance.

Additional acute and chronic toxicity studies completed subsequently for this project using the United States Environmental Protection Agency's standard whole effluent toxicity (WET) test [2] were completed in order to verify the validity of the test findings. Since WET testing is indicative for the salinity at which marine organisms would die, it was expected that the salinity tolerance level of 40 ppt established for the Carlsbad project using the STE test would be lower than the salinity level at which significant mortality occurs. The follow-up WET testing has confirmed this expectation and the validity of the new STE methodology. The WET testing using abalone *(Haliotis ruefescens)* showed that the chronic toxicity threshold for these species occurs for TDS concentration of over 40 ppt. Results from an acute toxicity test completed using another standard WET species, the topsmelt *(Atherinops affinis)* (see Fig. 6), indicates that the salinity in the discharge can reach over 50 ppt on a short-term basis (one day or more) without impacting this otherwise salinity-sensitive species. All test species survived salinity of 60 ppt for a period of 2 h.

The results of the salinity tolerance evaluation completed for the Carlsbad desalination project were well accepted by the state and local regulatory agencies (SanDiego and Santa Ana Regional Water Quality Control Boards) responsible for environmental protection in

Fig. 6. Topsmelt.

Table 3
Results of the salinity tolerance test

Special observed	Salinity (ppt)	Mortality	Elapsed time to first mortality (days)
Red abalones	33.5 (control tank)	0	N/A
Red abalones	37	0	N/A
Red abalones	38	0	N/A
Red abalones	39	0	N/A
Red abalones	40	0	N/A
Sand dollars	33.5 (control tank)	0	N/A
Sand dollars	37	0	N/A
Sand dollars	38	0	N/A
Sand dollars	39	0	N/A
Sand dollars	40	0	N/A
Purple sea urchins	33.5 (control tank)	1	1
Purple sea urchins	37	1	1
Purple sea urchins	38	1	4
Purple sea urchins	39	1	4
Purple sea urchins	40	1	6

N/A, not applicable.

California. These results were also used for the environmental review and permitting of the 50 MGD Huntington Beach desalination project, developed by Poseidon Resources in parallel with the Carlsbad project. In August 2006 both projects received permits to discharge their concentrate to ocean [9,10].

7. Conclusions

The STE methodology described allows determination of the maximum salinity (TDS) concentration which can be discharged by a seawater desalination plant without exerting significant environmental impact on the aquatic habitat in the area of the plant discharge. The maximum discharge salinity threshold is site-specific and depends on the type of species inhabiting the discharge area and the hydrodynamic conditions that govern the salinity dissipation process. The STE methodology was applied successfully to the environmental assessment of two large seawater desalination projects located in Carlsbad and Huntington Beach in Southern California. For the site-specific conditions of these projects, the TDS discharge threshold was determined to be over 40 ppt. The test species were able to survive salinities of over 50 ppt for a period of 2 days and 60 ppt for a period of 2 h.

Acknowledgments

The author wishes to recognize Dr. Jeffrey Graham and Dr. Scott Jenkins of Scripps Institution of Oceanography, University of California San Diego, and Dr. Steven LePage of M-REP Consulting, for their collaboration on this project.

References

[1] M.C. Mickley, Membrane Concentrate Disposal: Practices and Regulation, Desalination and Water Purification Research and Development Program Report N. 123, 2nd ed., US Department of Interior, Bureau of Reclamation, 2006.
[2] S.A. Jenkins and J. Wasyl, Hydrodynamic modeling of dispersion and dilution of concentrated seawater produced by the ocean desalination project at the Encina power plant, Carlsbad, California, Environmental Impact Report for Carlsbad Seawater Desalination Plant, City of Carlsbad, 2001.
[3] R. Einav and F. Lokiec, Environmental aspects of a desalination plant in Ashkelon, Desalination, 156 (2003) 79–85.
[4] California State Water Board, Procedures Manual for Conducting Toxicity Tests Developed by the Marine Bioassay Project,. 96-1WQ, 1996.
[5] G.A. Chapman, D.L. Denton and J.M. Lazorchak, Short-term methods for estimating the chronic toxicity of effluents and receiving waters to West Coast marine and estuarine organisms, USEPA Report No. EPA/600/R-95/136, 1996.
[6] C.I. Weber, W.B. Horning II, D.J. Klemm, T.W. Nieheisel, P.A. Lewis, E.L. Robinson, J. Menkedick and F. Kessler, Short-term methods for estimating the chronic toxicity of effluents and receiving waters to marine and estuarine organisms, EPA/600/4-87/028. National Information Service, Springfield, VA, 1998.
[7] S. Le Page, Salinity tolerance investigations: A supplemental report for the Carlsbad, CA desalination project, M-Rep Consulting, Environmental Impact Report for Carlsbad Seawater Desalination Plant, City of Carlsbad, 2004.
[8] J. Graham, Marine biological considerations related to the reverse osmosis desalination project at the Encina power plant, Carlsbad, CA, Environmental Impact Report for Carlsbad Seawater Desalination Plant, City of Carlsbad, 2004.
[9] San Diego RWQCB, Order No. R-9-2006-0065, NPDES No. CA 0109223, Waste discharge requirements for the Poseidon Resources Corporation Carlsbad desalination project, Discharge to the Pacific Ocean via the Encina power station discharge channel, 2006.
[10] Santa Ana RWQCB, Order No. R-8-2006-0034, NPDES No. CA 8000403, Waste discharge requirements for the Poseidon Resources (Surfside) LLC seawater desalination facility discharge to the Pacific Ocean, 2006.