SAB Ecological Processes and Effects Committee Augmented for Ballast Water Activities: Compilation of Draft Text

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Appendices for Section 5, part VI. Onshore Treatment

Appendix 1. Literature Review of Onshore Treatment Studies

Table A1-1 summarizes the various brief commentaries on and the relatively few analyses of onshore treatment that we found in ballast water reports and publications.

Table A1-1. Reports that discuss onshore treatment.

Report	Discussion	Conclusions
Pollutech 1992	Compares and ranks various shipboard and onshore treatment approaches.	Onshore ranks 2nd out of 24 options, ahead of all but one shipboard system.
AQIS 1993a	Compares shipboard, on-land and treatment ship approaches.	On-land and treatment ship are cheaper and more effective than shipboard.
AQIS 1993b	Briefly discusses treatment ship and on-land treatment.	Onshore treatment is unlikely except in special circumstances.
Aquatic Sciences 1996	Compares shipboard, treatment ship, on-land and external source treatment.	Onshore is technically feasible and the most effective and cheapest approach.
NRC 1996	Briefly discusses advantages and disadvantages of onshore treatment.	Onshore remains an option.
Gauthier & Steel 1996	Mentions shipboard, treatment ship and on-land approaches.	Onshore is considered a poor option.
Victoria ENRC 1997	Briefly discusses onshore treatment.	Onshore is probably too costly at a large scale; may be viable at a smaller scale.
Greenman et al. 1997	Student report commissioned by the U.S. Coast Guard, largely reprising AQIS 1993a.	
Cohen 1998	Briefly discusses advantages and disadvantages of onshore treatment.	Onshore has many advantages and few disadvantages compared to shipboard.
Reeves 1998, 1999	Briefly discusses onshore treatment.	Lists onshore as an alternative.
Oemke 1999	Briefly discusses advantages and disadvantages of onshore treatment.	Onshore is feasible for some parts of the industry, such as VLCCs.
Dames & Moore 1998, 1999	Briefly discusses onshore treatment.	Onshore may be good option at oil export terminals with oil stripping plants.
Cohen & Foster 2000	Briefly discusses advantages and disadvantages of onshore treatment.	
CAPA 2000	EPA-funded study estimates the cost of onshore treatment for California.	Onshore is technically feasible.
Rigby & Taylor 2001a,b	Briefly discusses onshore treatment.	Cost, availability, quality control may prevent onshore development, but it might work for tankers that discharge oily ballast to onshore facilities.
US EPA 2001	Briefly mentions onshore treatment.	
California SWRCB 2002	Briefly discusses onshore treatment.	Onshore is an attractive option, at least for some parts of the industry.

Glosten 2002	Estimates upper-bound retrofit costs to discharge ballast to onshore facilities.	
NSF 2003	Mentions shipboard, onshore and operational options for the longer term.	Shipboard seems the most challenging approach.
Brown and Caldwell 2007, 2008	Develops designs and estimates costs for onshore treatment at Milwaukee.	Onshore is feasible; treatment ship is cheaper than on-land.
California SLC 2009, 2010	Briefly discusses advantages and disadvantages of onshore treatment.	Onshore might be suitable for terminals with regular vessel calls such as cruise ships, or for the Port of Milwaukee.

Four studies compared the effectiveness or costs of onshore and shipboard ballast water treatment. In a study for the Canadian Coast Guard, Pollutech (1992) scored and ranked a variety of ballast water management approaches for vessels entering the Great Lakes, including ballast water exchange and several shipboard and onshore treatments, in terms of effectiveness, feasibility, maintenance and operations, environmental acceptability, cost, safety and monitoring. On-shore treatment with discharge to a sanitary sewer (the only onshore treatment scenario analyzed) ranked second out of 24 treatment and management approaches analyzed in the report.

AQIS (1993a) developed conceptual designs and cost estimates to compare shipboard, on-land and treatment ship approaches to treating the ballast water discharged from 140,000-ton bulk carriers carrying 45,000 MT of ballast water with a maximum ballast pumping rate of 4,000 MT/h, and an annual discharge of 500,000 MT. The shipboard system that was analyzed consisted of a 50-µm in-line strainer employed during ballasting, plus the installation of high-level ballast tank offtake pipes to reduce the discharge of ballast sediments and settled cysts or spore stages. The cost of pump upgrades that might be needed to address head loss from the strainers was not included. The on-land facility was designed to handle the discharge from three bulk carriers per week and included 52,000 MT storage capacity with coagulation, flocculation, granular filtration and UV disinfection at a maximum treatment rate of 830 MT/h, and thickening, dewatering and land-fill disposal of residual solids. The cost of land acquisition and the cost of pipes needed to carry ballast water from the berths to the treatment plant were not included. The treatment ship alternative was based on converting a used 12,500 DWT bulk carrier and installing 4,000 MT of storage capacity and a treatment system similar to the on-land system but with a maximum treatment rate of 4,000 MT/h and using pressurized granular filters. The cost estimates, including the cost of retrofitting cargo ships with pipe modifications and possible pump upgrades needed to allow discharge to an onshore treatment plant[1], are summarized in Table A1-2. Based on the annualized cost per 1,000 MT of ballast water, treatment in an on-land facility ($227-$348/1,000 MT) is thus less than half to about two-thirds of the cost of treating it in a shipboard plant ($529/1,000 MT). Treatment in a treatment ship is somewhat more or somewhat less expensive than treatment in a shipboard plant, depending on the utilization rate of the treatment ship (Table A1-2).

[1] Based on the estimated retrofit cost for a large bulk carrier (AQIS 1993a at p. 73) of $204,084 in June 2010 US dollars.

Table A1-2. Treatment cost estimates for shipboard, on-land and treatment ship approaches - single port scenario (AQIS 1993a). The figures have been adjusted to June 1, 2010 US dollars and annualized as described in Appendix 2. The number of ships is calculated as the number of bulk carriers (each discharging 500,000 MT/y) needed to discharge the stated annual treatment volume to the plant.

Treatment System	Number of Ships	Capital Costs: Storage	Capital Costs: Treatment	Capital Costs: Ship Retrofit	Operating Cost /1000 MT	Annualized Cost /1000 MT
Shipboard [1]	1	0	2,040,844	0	82	529
On-land [2]	11	3,061,266	6,122,532	2,244,928	92	227
On-land [3]	11	6,122,532	6,122,532	2,244,928	92	263
On-land [4]	11	3,061,266	16,326,752	2,244,928	92	348
Treatment ship [5]	14	8,673,587	12,755,275	2,857,182	422	700
Treatment ship [6]	23	8,673,587	12,755,275	4,693,941	276	458

[1] Treating 500,000 MT/y, or about 1 voyage/month.
[2] Treating 5,500,000 MT/y, with 52,000 MT storage in earthen basins and 830 MT/h treatment rate.
[3] Treating 5,500,000 MT/y, with 52,000 MT storage in steel tanks and 830 MT/h treatment rate.
[4] Treating 5,500,000 MT/y, with 4,000 MT storage in steel tanks and 4,000 MT/h treatment rate.
[5] Treating ≈3 ships/week (described as 40% utilization in AQIS 1993a), or 7,000,000 MT/y.
[6] Treating ≈5 ships/week (described as 70% utilization in AQIS 1993a), or 11,500,000 MT/y.

AQIS (1993a) also developed a scenario for onshore treatment of all the ballast water discharged in Australia (estimated at 66 million MT/y from at least 1,000 distinct ships) that included 3 treatment ships and 18 on-land treatment plants located in Australia's major ports, along with 16 barges to transport ballast water collected at smaller ports. The estimated total costs based on these assumptions are shown in Table A1-3. In this scenario the average annual ballast water discharge per ship is much smaller than in the single port scenario of Table A1-2, and the annualized costs per 1,000 MT are therefore larger. In this countrywide scenario, total shipboard treatment costs are about 4.4 times the total treatment costs onshore.

Table A1-3. Treatment cost estimates for shipboard and onshore approaches - Australia-wide scenario (AQIS 1993a). The figures have been adjusted to June 2010 US dollars and annualized as described in Appendix 2.

Approach	Capital Costs: Onshore Treatment Plants	Capital Costs: Treatment Ships	Capital Costs: Barges	Capital Costs: Shipboard Treatment or Retrofit	Operating Cost /1000 MT	Total Annualized Cost
Shipboard	–	–	–	2,040,844,000	82	228,879,179
Onshore	183,675,960	61,225,320	81,633,760	204,084,400	102	51,737,298

The study concluded that "land-based or port-based [=treatment ship] facilities are more economic and effective than numerous ship-board plants." In these estimates, some significant costs (pipes to transport ballast water from berths to treatment plants, and land costs) were not included in the onshore alternatives which reduced their estimated total cost relative to the shipboard alternative. On the other hand, the onshore treatment approach (using granular filtration with coagulation and flocculation followed by UV disinfection) would treat ballast water to a substantially higher standard than the shipboard alternative (using only a 50 µm strainer with no disinfection); and for the single-port scenario, basing the analysis on large bulk carriers, which typically discharge the largest volumes of ballast water of the vessels using Australia's ports (Table 4.1 in AQIS 1993a), greatly favored shipboard treatment. The estimates are also somewhat sensitive to other factors, including the assumed utilization rates for the onshore systems, and the interest rate used to annualize costs.

In a second study conducted for the Canadian Coast Guard, Aquatic Sciences (1996) considered onshore treatment alternatives (referred to as "pump off options") for Great Lakes shipping and found them to be "technically feasible" and to "undoubtedly offer the best assurance of prevention of unwanted introductions." The report further found that when installed onshore, "treatment options could have a more practical and enforceable application" than in shipboard installations, and concluded that "ship board treatment of ballast water appears to be logistically, economically, and particularly from the aspect of control, the least attractive method of ballast water treatment." The report estimated that treatment ships could be provided at key ports throughout the Great Lakes to receive discharged ballast water and heat it to >65°C at an annualized cost of around $17 million to (more likely) $51 million, or alternately a single treatment ship could operate at a site en route to the Great Lakes to treat all incoming ballast water at a annualized cost of $2.7-2.8 million. Retrofitting costs to enable ships to discharge their ballast water to treatment ships could range from around $40,000 to over $200,000 per ship.[2]

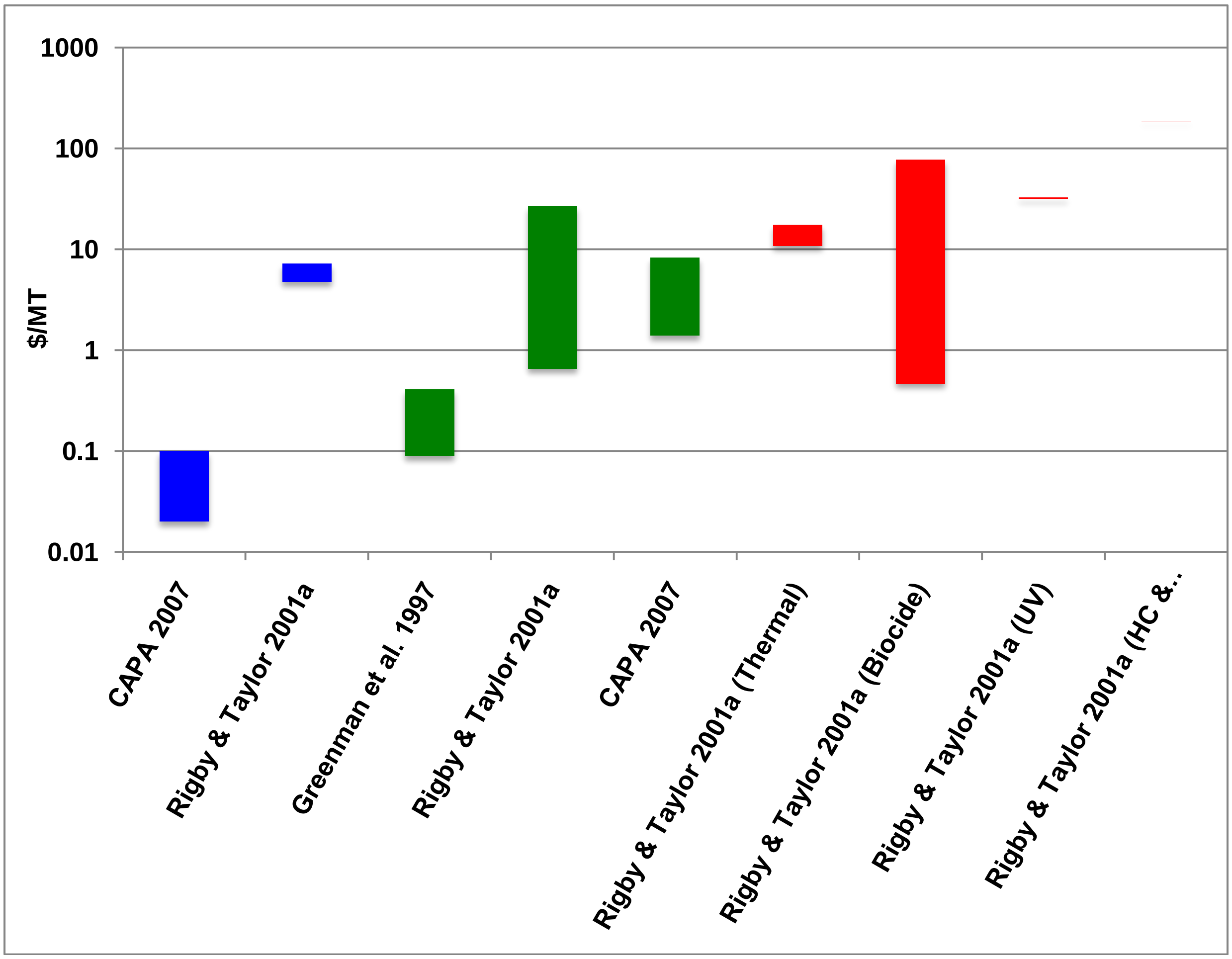
California's State Water Resources Control Board (California SWRCB 2002) conducted a qualitative evaluation of onshore treatment and ten shipboard treatment alternatives in terms of effectiveness, safety, and environmental acceptability. Onshore treatment was the only approach to be rated acceptable in all three categories. There were reservations or unresolved questions about the effectiveness of all of the shipboard alternatives, about the safety of eight of the shipboard alternatives, and about the environmental acceptability of nine of the shipboard approaches.

In each of these studies, onshore treatment was judged to be as effective or more effective, and generally cheaper, than shipboard treatment. As noted, there are limitations to these studies and grounds for criticism, however the first three appear to be the most detailed comparisons of onshore and shipboard treatment approaches available. In addition, the U.S. Coast Guard compiled a table of cost estimates from different studies for public review and comment (U.S. Coast Guard 2002). Figure A1-1 shows all the estimates that were expressed in the table as costs per metric ton or cubic meter of ballast water, and thus in a form that can be compared. In these estimates, onshore treatment is generally more expensive than ballast water exchange and less

[2] The costs cited in this paragraph were adjusted to June 1, 2010 US dollars as described in Appendix 1.

expensive than shipboard treatment, though there is considerable overlap.

Figure A1-1. Cost estimates listed in U.S. Coast Guard (2002). The Coast Guard converted Australian estimates to U.S. dollars at the Oct. 16, 2001 exchange rate, but did not adjust estimates for inflation. Cost estimates for ballast water exchange are in blue, for onshore treatment in green, and for shipboard treatment in red.



The other comparisons of onshore and shipboard treatment in the literature consist of lists or brief discussions of their relative merits. These reports variously conclude that onshore treatment is probably a superior or probably an inferior option compared to shipboard treatment, or that onshore treatment is suitable for a particular part of the cargo fleet (Table A1-1), but none provide any significant analysis or data to support these conclusions. Gauthier & Steel (1996) stated that onshore treatment is "considered a poor option," citing Pollutech (1992) who drew no such conclusion but rather ranked onshore treatment higher than nearly all shipboard approaches. Dames & Moore (1999) stated that onshore treatment is "considered to be less favorable than on-board treatment options" without saying who considered it so; Dames & Moore (1998) identified the source of this opinion as Oemke (1999),[3] who however made no such statement.[4]

Two studies (in addition to AQIS (1993a) and Aquatic Sciences (1996), discussed above) provide conceptual designs and cost estimates for onshore treatment for specific regions. CAPA (2000) is an EPA-funded study conducted for the California Association of Port Authorities. This study developed conceptual designs and cost estimates for constructing and operating ballast water treatment plants at each cargo port in California. These plans and estimates include the piping from berths to plants; storage tanks; coagulation, flocculation, filtration and UV disinfection; thickening, dewatering and land-fill disposal of residual solids; and discharge of effluent through an outfall pipeline; they did not include land costs, permitting, seismic evaluation, or costs to retrofit vessels to enable them to discharge ballast water to an onshore facility. The study concluded that onshore treatment would be technically and operationally feasible, though there could be delays to some vessels in some circumstances. The estimated costs are shown in Table A1-4.

Table A1-4. Cost estimates for onshore treatment in California (CAPA 2000). The figures have been adjusted to June 1, 2010 US dollars and annualized as described in Appendix 2.

	— — — Capital Costs — — —					
Port	**Pipes**	**Storage Tanks**	**Treatment Plant**	**Outfall**	**Annual O&M**	**Annualized Costs**
Hueneme [1]	1,325,069	69,014	0	125,480	0	98,850
Humboldt Bay	15,900,826	5,019,200	2,234,799	125,480	187,969	1,702,386
Long Beach	35,909,364	6,399,480	2,786,158	125,480	280,390	3,222,047
Los Angeles	33,921,761	25,597,920	2,786,158	125,480	280,390	4,341,637
Oakland	19,876,032	4,768,240	2,234,799	125,480	187,969	1,944,654
Redwood City	1,987,603	5,395,640	2,047,206	125,480	178,684	800,310
Richmond	7,287,878	4,266,320	2,047,206	125,480	178,684	1,071,637
Sacramento	1,722,589	6,023,040	2,047,206	125,480	178,684	823,884
San Diego	11,660,605	3,889,880	2,047,206	125,480	178,684	1,331,601
San Francisco	10,600,550	7,905,240	2,234,799	125,480	187,969	1,545,337
Stockton	6,757,851	6,901,400	2,047,206	125,480	178,684	1,208,574
California	146,950,130	76,235,374	22,512,743	1,380,280	2,018,105	18,090,918

[1] CAPA (2000) concluded that building a treatment plant at Port Hueneme made no sense because so little ballast was discharged there (<2 MT/d), and that instead the ballast water could be "discharged to the sewer, reballasted to an outgoing ship, taken to another port for treatment,...transported by a separate vessel for discharge at sea" or batch treated with chlorine. The report estimated piping, storage and outfall costs for this site, but did not estimate treatment plant costs.

[3] Cited "in review" in 1998.

[4] Oemke (1999) cited several advantages of onshore treatment (use of treatments not feasible on ships, easy adjustment of pH to optimal treatment conditions, easy removal of oxidant residuals), noted that it is a "very attractive" option for the VLCC portion of the fleet, but suggested that it will not be widely used otherwise because of ships' practice of partially deballasting while approaching berths.

Brown and Caldwell (2007, 2008) developed designs and cost estimates for on-land and treatment ship approaches to treating the ballast discharges from oceangoing ships arriving at the Port of Milwaukee. The first report assessed four on-land treatment systems:

- 100-µm screening followed by UV treatment;
- coarse screening followed by ozonation;
- 500-µm screening followed by membrane filtration to remove particles >0.1 µm;
- 500-µm screening followed by hydrodynamic cavitation.

These were each analyzed along with two systems for transferring and storing the discharged ballast water: discharge at berths into pipes that carry the water to on-land storage tanks and a treatment plant; and discharge to a barge that stores the water and carries it to an on-land treatment plant. Design criteria assumed 85 ship arrivals during the eight months that the St. Lawrence Seaway is open each year, and a system capable of receiving ballast water at 680 MT/h, with storage capacity of 1,900 MT, and treatment at 80 MT/h. Estimated costs are shown in Table A1-5. The report concluded that all four treatment systems and both transport/storage systems are feasible, with UV treatment and hydrodynamic cavitation having the most promise for treating viruses (Brown and Caldwell 2007). The second report (Brown and Caldwell 2008) developed a design and cost estimate for retrofitting a barge to serve as a treatment ship, which would collect, store and treat ballast water. The treatment system included a cloth media disk filter with a nominal pore size of 10 µm, and UV treatment at an estimated minimum dose of 30 mJ/cm^2. The design criteria for this analysis required the capacity to receive ballast discharges at 2,300 MT/h, storage of 10,000 MT, and treatment at 230 MT/h, thus around 3 times the flow rates and 5 times the storage required in the first report. The cost estimates for the eight on-land treatment alternatives analyzed in the first report, adjusted to meet the more demanding design criteria used in the second report, plus the cost estimates for the treatment ship in the second report, are shown in Table A1-6.

Table A1-5. Cost estimates for onshore treatment for oceangoing ships at the Port of Milwaukee (Brown and Caldwell 2007). The figures have been adjusted to June 1, 2010 US dollars and annualized as described in Appendix.2.

	— —	Capital Costs	— —		
Treatment (Transport) [1]	**Pipes [2]**	**Storage**	**Treatment**	**Annual O&M**	**Annualized Costs**
100-µm screening & UV (pipes)	2,973,120	1,251,840	584,192	13,986	399,885
Ozone (pipes)	2,973,120	1,251,840	834,560	9,806	415,795
0.1-µm membrane filter (pipes)	2,973,120	1,251,840	1,043,200	19,917	442,648
Hydrodynamic cavitation (pipes)	2,973,120	1,251,840	2,608,000	20,864	569,158
100-µm screening & UV (barge) [3]	260,800	521,600	584,192	369,166	478,825
Ozone (barge) [3]	260,800	521,600	834,560	364,985	494,734
0.1-µm membrane filter (barge) [3]	260,800	521,600	1,043,200	375,096	521,587
Hydrodynamic cavitation (barge) [3]	260,800	521,600	2,608,000	376,043	648,098

[1] Design criteria are: maximum ballast discharge of 680 MT/h, storage of 1,900 MT, and treatment rate of 80 MT/h; "(pipes)" refers to discharge of ballast water at berths into a pipe system connecting to the treatment plant;

"(barge)" refers to discharge to a barge to transport the ballast water to the treatment plant.
[2] Includes collection pumps, pipes and a lift/coarse screening station.
[3] "Storage" refers to barge purchase and modification costs for use as transfer and storage vessel, exclusive of treatment system.

Table A1-6. Cost estimates for onshore treatment for oceangoing ships at the Port of Milwaukee (Brown and Caldwell 2007, 2008). The figures for the eight alternatives analyzed in Brown and Caldwell (2007) have been adjusted to meet the design criteria of Brown and Caldwell (2008) as described in Appendix 3. All figures have been adjusted to June 1, 2010 US dollars and annualized as described in Appendix 2.

	— — Capital Costs — —				
Treatment (Transport) [1]	**Pipes [2]**	**Storage**	**Treatment**	**Annual O&M**	**Annualized Costs**
100-µm screening & UV (pipes)	5,384,924	3,546,880	1,669,120	13,986	864,632
Ozone (pipes)	5,384,924	3,546,880	2,384,457	9,806	917,852
0.1-µm membrane filter (pipes)	5,384,924	3,546,880	2,980,571	19,917	975,797
Hydrodynamic cavitation (pipes)	5,384,924	3,546,880	7,421,623	20,864	1,333,105
100-µm screening & UV (barge) [3]	794,819	1,043,200	1,669,120	369,166	650,588
Ozone (barge) [3]	794,819	1,043,200	2,384,457	364,985	703,808
0.1-µm membrane filter (barge) [3]	794,819	1,043,200	2,980,571	375,096	761,753
Hydrodynamic cavitation (barge) [3]	794,819	1,043,200	7,421,623	376,043	1,119,061
10-µm filter & UV (treatment ship) [3]	0	2,695,184	808,854	518,914	800,087

[1] Design criteria are: maximum ballast discharge of 2,300 MT/h, storage of 10,000 MT, and treatment rate of 230 MT/h; "(pipes)" refers to discharge of ballast water at berths into a pipe system connecting to the treatment plant; "(barge)" refers to discharge to a barge to transport the ballast water to the treatment plant.
[2] Includes collection pumps, pipes and a lift/coarse screening station.
[3] "Storage" refers to barge purchase and modification costs for use as transfer and storage vessel or as treatment ship, exclusive of treatment system.

Besides the need for facilities to receive and transport ballast water from ships, store it and treat it, ships must be modified so they can safely and rapidly discharge ballast water to onshore facilities. There have been several estimates of the costs of these retrofits (Table A1-7), which require modifications in a ship's pipe system and may require the installation of larger ballast pumps (in order to raise the water to deck level, and/or to discharge it quickly enough). These costs may vary between different types and sizes of ships, with the costs ranging from around $15,000 to $540,000 for container ships (Pollutech 1992; Glosten 2002), from around $15,000 to $500,000 for bulkers (Pollutech 1992; CAPA 2000), and from considerably less than $140,000 to around $2.3 million for tankers (Victoria ENRC 1997; Glosten 2002) (Fig. A1-2). Most of these estimates specifically included costs for replacing existing pumps with more powerful pumps where needed (AQIS 1993a; Aquatic Sciences 1996; Dames & Moore 1998; CAPA 2000;

Glosten 2002[5]; Brown and Caldwell 2008[6]). The estimated cost to outfit a new ship would be less than the cost to retrofit a comparable existing ship (AQIS 1993b), perhaps by as much as an order of magnitude (CAPA 2000).

Table A1-7. Cost estimates for retrofitting ships to discharge ballast water to a treatment facility. The figures have been adjusted to June 1, 2010 US dollars as described in Appendix 2. In the parentheses following the ship type, length is given in feet, size in deadweight tons (DWT), ballast water capacity in metric tons (MT), and maximum ballast discharge rate in metric tons per hour (MT/h), if stated.

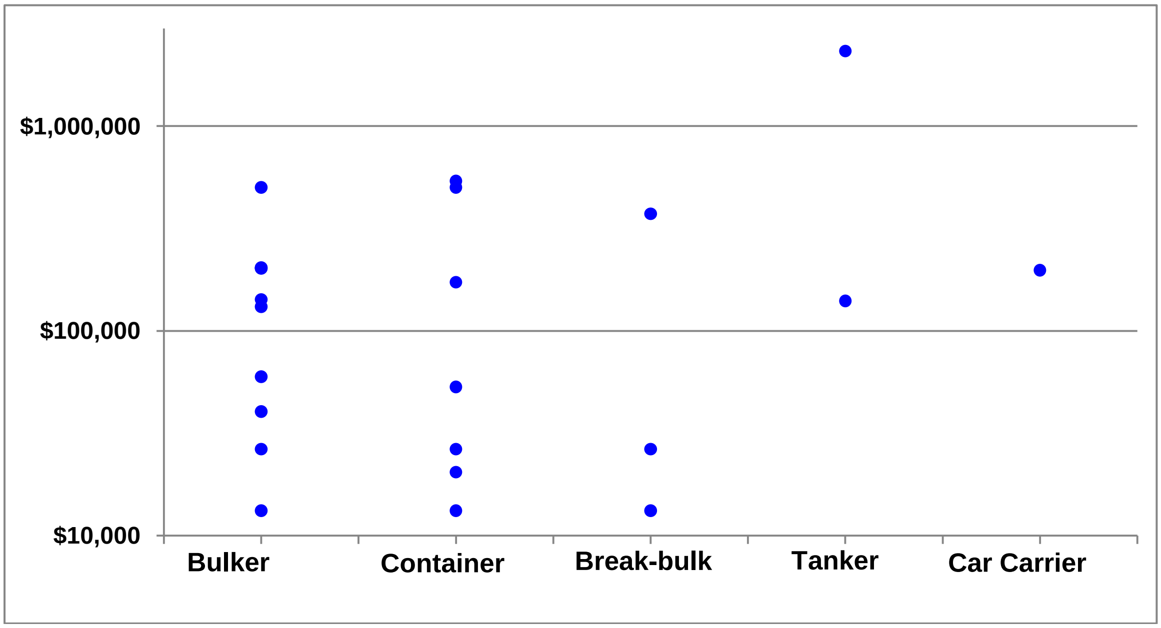
Ship Type	Capital Cost	Report
Great Lakes bulker, break-bulk or container	$13,233–26,465	Pollutech 1992
Small container	$20,408	AQIS 1993a
Large bulker (140,000 DWT; 45,000 MT; 4,000 MT/h)	$204,084	AQIS 1993a
Great Lakes bulker	$40,352–201,758	Aquatic Sciences 1996
Handysize bulker (520'; 22,000 DWT)	$142,340	Victoria ENRC 1997
Container	$53,196-172,887	Dames & Moore 1998 [1]
Container or bulker (1,000 MT/h)	$501,920	CAPA 2000
Tanker (869'; 123,000 DWT; 75,850 MT; 6,400 MT/h)	$2,328,607	Glosten 2002
Bulker (735’; 67,550 DWT; 35,000 MT; 2,600 MT/h)	$131,316	Glosten 2002
Break-bulk (644'; 40,300 DWT; 26,850 MT; 3,000 MT/h)	$373,394	Glosten 2002
Container (906'; 65,480 DWT; 19,670 MT; 2,000 MT/h)	$539,539	Glosten 2002
Car carrier (570'; 13,847 DWT; 6,600 MT; 550 MT/h)	$197,773	Glosten 2002
Bulker (469’; 5,700 MT; 570 MT/h)	$59,694	Brown and Caldwell 2008
Bulker (722’; 18,000 MT; 2,300 MT/h)	$202,960	Brown and Caldwell 2008

[1] Estimate developed by the Pacific Merchant Shipping Association.

[5] Glosten (2002) designed the pumps and pipe systems to be large enough to enable ships to deballast completely at berth during a typical cargo loading period.

[6] Brown and Caldwell (2008) found, based on pump and pipe system curves (dynamic head vs. flow), that the small and large Great Lakes bulk carriers they analyzed would not need larger ballast pumps—that is, with their existing pumps the ships could fully deballast while at berth during the time it takes to load cargo.

Figure A1-2. Cost estimates for retrofitting ships to discharge ballast water to a treatment facility. The figures have been adjusted to June 2010 US dollars as described in Appendix 2. Some estimates apply to more than one ship type, and appear in more than one column in the figure.



Some of these reports provide little or no supporting data or explanation for the cost estimates (Pollutech 1992; AQIS 1993a; Aquatic Sciences 1996; Dames & Moore 1998). Victoria ENRC (1997) provided a materials list for a bulk carrier, and noted that a tanker "with its ballast lines running on deck would have a considerable lower installation cost." CAPA (2000) provided a cost-breakdown for modifying a bulk carrier, and stated that modifying a tanker would generally cost more.

Glosten (2002) and Brown and Caldwell (2008) provided the most recent and most detailed estimates. Glosten (2002) estimated ship modification costs for ballast water transfer systems on five ships representing common types of vessels calling at Puget Sound ports (Table A1-6). These systems were designed to "allow ballast transfer with minimal disruption to current operations," including sizing them to allow vessels to deballast completely at berth during the time needed to complete cargo loading, thereby eliminating the need to start deballasting before arriving at berth. To represent each vessel category, the authors selected ships that "had ballast systems with capacities on the upper end of vessels that call on Puget Sound to attempt to establish an upper-bound on retrofitting costs." In addition, in selecting pipe sizing and other design elements, "every attempt was made to capture an upper bound on the modification costs associated with each vessel type surveyed." This included the installation of "a completely new piping system to provide the ability to fill and empty each ballast tank separately." Notably, this new piping system was included even though it is not needed on crude oil tankers, the type of tanker analyzed (which produced by far the highest cost estimate in the study), where "a simpler, lower-cost solution" exists, because it might be needed on some other ships (i.e. product tankers) in the same general category.[7] The transfer systems were also designed to allow ballast water transfer in either direction between a ship and an onshore facility (either onto or off a ship),[8] which in some cases may raise the cost over what is needed to only discharge ballast water to onshore facilities.

Brown and Caldwell (2008) provided analyses, conceptual designs, schematic drawings and cost estimates for modifying two sizes of ocean-going bulk carriers serving the Great Lakes, based a smaller, actual ship and a larger hypothetical ship (Table A1-6). These designs were also sized to allow the ship to initiate and complete deballasting at berth during cargo loading.

In addition to discussions or analyses of onshore treatment in reports, the potential for treating ballast discharges onshore has been recognized in laws, regulations, guidelines and treaty conventions. The U.S. Nonindigenous Aquatic Nuisance Prevention and Control Act (NANPCA) of 1990 and the National Invasive Species Act (NISA) of 1996 directed the U.S. Coast Guard to fund research on ballast water management, specifically noting that technologies in "land-based ballast water treatment facilities" could be included, and to investigate the feasibility of using or modifying onshore ballast water treatment facilities used by Alaskan oil tankers to reduce the introduction of exotic organisms (§§1101(k)(3), 1104(a)(1)(B), 1104(a)(2) and 1104(b)(3)(A)(ii) in U.S. Congress 1990, 1996). In its interim and final rules implementing NISA, the U.S. Coast Guard specifically included discharge to an onshore treatment facility as a means of meeting NISA's ballast discharge requirements, and required ships to keep records of ballast water discharged to such facilities (US Coast Guard 1999, 2001), although the Coast Guard eliminated these provisions when it concluded that it did not have the authority to regulate or approve onshore ballast water treatment plants (US Coast Guard 2004). The U.N. International Maritime Organization's 1991 Guidelines state that "Where adequate shore reception facilities exist, discharge of ship's ballast water in port into such facilities may provide an acceptable means of control" (IMO 1991 and IMO 1993, §7.5 Shore Reception Facilities). The IMO's 1997 Guidelines state that "Discharge of ship's ballast water into port reception and/or treatment facilities may provide an acceptable means of control. Port State authorities wishing to utilize this strategy should ensure that the facilities are adequate...If reception facilities for ballast water and/or sediments are provided by a port State, they should, where appropriate, be utilized" (IMO 1997, §7.2.2, §9.2.3). The IMO's 2004 Convention states that "The requirements of this regulation do not apply to ships that discharge ballast water to a reception facility designed taking into account the Guidelines developed by the Organization for such facilities" (IMO 2004, Regulation B-3.6). The IMO adopted specific guidelines for onshore ballast water treatment facilities (IMO 2006), and also recognized onshore treatment as an alternative in IMO 2005b

[7] This is consistent with the study's stated aim, to quantify "the capital cost required to provide the maximum capability in a ballast transfer system, to represent a maximum capital investment" for each vessel category (Glosten 2002).

[8] The ability to move ballast water onto a ship from an onshore service was included to accomodate the possibility of loading "clean" ballast, an approach that is not considered to be onshore treatment in this report.

(§1.2.3), as do Australia, New Zealand and Canada in their ballast water regulations (AQIS 1992; New Zealand 1998, 2005; Canada 2000, 2007).

Additional Information on comparisons of shipboard and onshore treatment

Trained personnel

AQIS (1993a) noted that in shipboard systems "treatment equipment would be subject to operation, repair and maintenance by the crew. With the standards of ship maintenance in some cases having slipped badly for the both hull and machinery, it may be assumed in these cases that ballast water treatment systems would not be accorded a high priority for maintenance and could be easily by-passed or operated at sub-optimal efficiency." Aquatic Sciences (1996) noted with regard to shipboard treatment that "crew standards with respect to operating and maintenance capability in the deep sea fleet are unpredictable at best....there are no guarantees of their effectiveness...Filtration, strainers, or other high maintenance systems are particularly vulnerable" and "are least likely to stay in service particularly in shipboard applications." California SWRCB (2002) concluded that "a landbased treatment facility operated by professional wastewater treatment specialists would allow a better control of the treatment processes." Brown and Caldwell (2007, 2008) concluded that one advantage of onshore treatment "operated and maintained by experienced treatment operators" is "better control in ensuring that the desired level of ballast water treatment occurs."

Reliability

In a section titled "The Virgin Tank," Reeves (1998) explains that "the concept is that water will always be treated in-stream at the time of intake and the tank will be maintained in a consistently pristine condition...The problem with this appealing concept is that one filter breakthrough or failure to religiously maintain and use the system...throughout the voyages around the world to ports such as Bombay and Naples by a foreign crew will contaminate the tank and vitiate the protection to be achieved when the vessel later shows up in a U.S. or Canadian port."

Safety

AQIS (1993a) concluded that "the control of occupational health and safety issues would...provide the most difficulty in shipboard systems, particularly if hazardous chemicals are involved," and also noted concerns regarding "hazardous environments created by the treatment equipment, e.g. heat, UV, mechanical movements," etc. on board ships. Lloyd's Register (1995, cited in Reeves 1998) stated that "both inorganic and organic biocides would present a range of health and safety problems related to storage of chemicals, compatibility with cargo carried on board as well as direct and indirect handling of chemicals by crew members." The National Research Council (1996) noted that while "safety issues associated with handling chemicals on board a ship may be of concern," the volume of such chemicals may be small and it should be possible to train ships' crews to handle them safely. Cohen (1998) noted "concerns about crew safety or wear or stress on the ship (*i.e.* concerns over storage and use of toxic chemicals, corrosion or thermal stresses that arise with various on-board treatments).” Regarding the risk of environmental damage, Pollutech (1992) observed that “the risk of a spill [in onshore plants] would be less than that for all vessels carrying the same chemicals.”

Compliance

AQIS (1993b) reported that one advantage of onshore treatment is that it is “the only arrangement where:

- responsibility for monitoring, control and effectiveness is totally in the hand of authorities at the destination port;
- beneficiaries of treatment (coastal water users, fisheries and aquaculture industries etc.) have physical evidence of controls in place;
- there is no reliance on actions from originating port authorities or ship operators to ensure that treatment is effective.”

Both Dames & Moore (1999) and California SWRCB (2002) noted the value of having the receiving port authorities be responsible for the operation and maintenance of treatment systems. Dames & Moore (1999) noted that onshore treatment removed “the need for reliance on ships’ logs (which can potentially be falsified).” Aquatic Sciences (1996) recommended that new initiatives in ballast water treatment “focus on compliance, enforcement and monitoring issues as a major driving force in the selection criteria.”

Cost recovery

Of the studies that mention cost recovery, the only actual discussion of the issue (beyond a few word mention of it) appears to be in Cohen & Foster (2000), as follows: “One question that arises with on-shore treatment is who would pay for the construction and operation of treatment facilities, the ships or the ports? If ships were required to treat their ballast water discharges and onshore treatment was the cheapest approach, either shipping companies, ports or, conceivably, independent entrepreneurs might choose to construct treatment facilities. If ports or independent parties were to do so, they could recover costs and turn a profit by charging ships appropriate fees for receiving and treating their ballast water. A potential advantage to the shipping industry of on-shore treatment is that plant construction costs are more likely to be subsidized by federal or state governments—just as the cost of constructing wastewater treatment plants was subsidized during the implementation of the Clean Water Act—than would the cost of constructing or installing treatment plants on board ships. For example, low-interest or no interest loans are available for the construction of on-shore facilities to treat ballast water in California, through the State Revolving Fund administered by the State Water Resources Control Board, which is a form of subsidy.”

Cost of redundancy

Relative costs will make this far more difficult in shipboard systems, due to the large difference in the core treatment capacity need in shipboard vs. onshore applications (Table VI B 2). Because of this, adding extra capacity (e.g., 30%) to each treatment plant to provide redundancy in case part of the system breaks down or is taken offline for maintenance would entail a much greater industry-wide cost for shipboard than for onshore treatment approaches, even without considering the added costs due to shipboard space constraints.

Achievable levels of reductions for different treatment methods

Tables A1-3 through A1-5 provide information on the extent of reduction possible for protists, bacteria and viruses with different types of onshore treatment systems. Table A1-6 shows the level of reduction achieved in current shipboard treatment systems.

Table A1-8. Examples of achievable log reductions for protists.

Treatment	Parameter	Log reduction	Reference
EXISTING STANDARDS			
US EPA requirement for drinking water treatment, depending on the quality of the source water	*Giardia*	3-5	US EPA 1991
FILTRATION AND/OR SEDIMENTATION PROCESSES			
Coagulation-flocculation-sedimentation-filtration	*Cryptosporidium*	2	LeChevallier & Au 2004
Coagulation-flocculation-sedimentation-filtration	*Giardia*	3-3.6	US EPA 1991, 1997b; LeChevallier & Au 2004
Coagulation-flocculation-sedimentation-filtration	protozoa	≥4	LeChevallier & Au 2004
Coagulation-flocculation-dual media filtration	*Cryptosporidium*	≥2.3	LeChevallier & Au 2004
Coagulation-flocculation-dual media filtration	*Giardia*	≥3.3	LeChevallier & Au 2004
Dissolved air flotation	protozoa	3	WHO 2008
Granular filtration	*Cryptosporidium*	≥2.7	LeChevallier & Au 2004
Granular filtration	*Giardia*	≥4.4	LeChevallier & Au 2004
Granular high-rate filtration	protozoa	3	WHO 2008
Slow sand filtration	*Giardia*	4	US EPA 1997b
Slow sand filtration	*Cryptosporidium*	3	LeChevallier & Au 2004
Slow sand filtration	*Cryptosporidium*	>4	NESC 2000a
Bank infiltration	protozoa	4	WHO 2008
Bank infiltration	algae & diatoms	4.8-7.2	LeChevallier & Au 2004
High-rate clarification	algae	3.9	LeChevallier & Au 2004
High-rate clarification	diatoms	4.5	LeChevallier & Au 2004
High-rate clarification	protozoa	4	WHO 2008
Pre-coat filtration	protozoa	4	WHO 2008
Microfiltration (0.2 µm)	*Cryptosporidium*	5.3	LeChevallier & Au 2004
Microfiltration (0.2 µm)	algae	6.4	LeChevallier & Au 2004
Microfiltration (0.2 µm)	*Giardia*	>6	LeChevallier & Au 2004
Microfiltration (0.2 µm)	*Cryptosporidium*	>6	LeChevallier & Au 2004
Microfiltration or ultrafiltration	*Giardia*	>5-6	NESC 1999
Microfiltration or ultrafiltration	*Cryptosporidium*	>4.4 to >6.9	LeChevallier & Au 2004
Microfiltration or ultrafiltration	*Giardia*	>4.7 to >7.0	LeChevallier & Au 2004
Microfiltration or ultrafiltration	protozoa	complete removal	LeChevallier & Au 2004
Nanofiltration or reverse osmosis	*Giardia*	complete removal	NESC 1999
Microfiltration, ultrafiltration, nanofiltration or reverse osmosis	*Giardia*	complete removal	US EPA 1997b
Ultrafiltration, nanofiltration or reverse osmosis	protozoa	complete removal	WHO 2008
BIOCIDES			
Ozone with 5 min. contact	*Giardia*	3	US EPA 1997b
UV DISINFECTION			
UV at 5 mWs/cm^2	*Giardia*	2	WHO 2008
UV at 10 mWs/cm^2	*Cryptosporidium*	3	LeChevallier & Au 2004

Table A1-9. Examples of achievable log reductions for bacteria.

Treatment	Parameter	Log reduction	Reference
FILTRATION AND/OR SEDIMENTATION PROCESSES			
Coagulation-filtration	total & fecal coliform	3	Wang et al. 2006
Coagulation-flocculation-sedimentation-filtration	*Clostridium perfrigens*	3.1	LeChevallier & Au 2004
Slow sand filtration	total coliform	4	LeChevallier & Au 2004
Pre-coat filtration	bacteria	3	WHO 2008
4-m bankside infiltration	bacteria	≥4	WHO 2008
Microfiltration (0.2 µm)	heterotrophic bacteria	3.3	LeChevallier & Au 2004
Microfiltration (0.2 µm)	total coliform	4.3	LeChevallier & Au 2004
Microfiltration	bacteria	4	WHO 2008
Microfiltration	*Bacillus subtilis*	5.6-5.9	LeChevallier & Au 2004
Microfiltration plus nanofiltration	*Bacillus subtilis*	8-11	LeChevallier & Au 2004
Ultrafiltration	total & fecal coliform	≥6-7	Wang et al. 2006
Ultrafiltration (0.01 µm)	total coliform	≥7	LeChevallier & Au 2004
Nanofiltration or reverse osmosis	bacteria	complete removal	US EPA 1997b
Ultrafiltration, nanofiltration or reverse osmosis	bacteria	complete removal	WHO 2008
BIOCIDES			
3 mg/l chlorine (20 min. contact)	total & fecal coliform	3-4	Wang et al. 2006
4.5 mg/l chlorine (20 min. contact)	total & fecal coliform	≥5-6	Wang et al. 2006
0.1-0.2 mg/l ozone (1 min. contact)	*Mycobacterium avium*	3	LeChevallier & Au 2004
0.11 mg/l ozone (15 min. contact)	total & fecal coliform	4	Wang et al. 2006
1 mg/l ozone (15 min. contact)	total & fecal coliform	5-6	Wang et al. 2006
UV DISINFECTION			
UV at 0.65 mWs/cm^2	*Vibrio cholerae*	4	LeChevallier & Au 2004
UV at 20 mWs/cm^2	*Streptococcus sp., Vibrio anguillarum, Pasturella piscicida*	3	Sugita et al. 1992
UV at 20 mWs/cm^2	*Escherichia coli*	4	LeChevallier & Au 2004
UV at 30 mWs/cm^2	*Salmonella typhi*	4	LeChevallier & Au 2004
UV at 31 mWs/cm^2	*Bacillus subtilis* spores	4	LeChevallier & Au 2004
UV at 60-90 mWs/cm^2	*Bacillus subtilis*	4	US EPA 1997b

Table A1-10. Examples of achievable log reductions for viruses.

Treatment	Parameter	Log reduction	Reference
EXISTING STANDARDS			
US EPA requirement for drinking water treatment, depending on the quality of the source water	viruses	4-6	US EPA 1991
FILTRATION AND/OR SEDIMENTATION PROCESSES			
Flocculation-sedimentation	viruses	2.5	Guy et al. 1997
Coagulation-filtration	Coxsackie B3 virus	2	Wang et al. 2006
Coagulation-flocculation-sedimentation-filtration	viruses	3	US EPA 1991
Coagulation-flocculation-sedimentation-filtration	somatic coliphage	3.5	LeChevallier & Au 2004
Granular high-rate filtration	viruses	3	WHO 2008
4-m bank infiltration	viruses	4	LeChevallier & Au 2004; WHO 2008
Slow sand filtration	viruses	4	WHO 2008
Flocculation-sedimentation-rapid sand filtration-activated charcoal column-chlorination	viruses	>5.3	Guy et al. 1997
Microfiltration (0.2 µm)	total culturable virus	2.7	LeChevallier & Au 2004
Microfiltration (0.2 µm)	male-specific coliphage	3.7	LeChevallier & Au 2004
Ultrafiltration (0.01 µm)	MS-2 bacteriophage	≥6	LeChevallier & Au 2004
Ultrafiltration (0.01 µm)	MS-2 bacteriophage	≥6.5	LeChevallier & Au 2004
Nanofiltration or reverse osmosis	viruses	complete removal	US EPA 1997b; NESC 1999
Ultrafiltration at lower pore sizes, nanofiltration or reverse osmosis	viruses	complete removal	WHO 2008
BIOCIDES			
1 mg/l ozone (15 min. contact)	Coxsackie B3 virus	4	Wang et al. 2006
Ozone (5 min. contact)	enteric viruses	4	US EPA 1997b
Ozone (≈5 sec. contact)	MS-2, Hepatitis A	>3.9 to >6	US EPA 1997b
Lime softening at pH>11	viruses	4	WHO 2008
UV DISINFECTION			
UV at 6-16 mWs/cm^2	Hepatitis A	4	LeChevallier & Au 2004
UV at 23-30 mWs/cm^2	Poliovirus	4	LeChevallier & Au 2004
UV at 30 mWs/cm^2	Coxsackie AZ virus	4	LeChevallier & Au 2004
UV at ≈30 mWs/cm^2	Rotavirus	3	US EPA 1997b
UV at ≈ 40 mWs/cm^2	Rotavirus	4	US EPA 1997b
UV at 40-50 mWs/cm^2	Rotavirus	4	LeChevallier & Au 2004
UV at 60-90 mWs/cm^2	MS-2 bacteriophage	4	US EPA 1997b
UV at 50-100 mWs/cm^2	MS-2 bacteriophage	4	LeChevallier & Au 2004
UV at 90-140 mWs/cm^2	viruses	4	NESC 2000b
UV at 186 mWs/cm^2	Adenovirus	4	LeChevallier & Au 2004

Table A1-11. Log changes demonstrated in tests of type-approved shipboard ballast water treatment systems.

Treatment	Test Conditions	Plankton >50 µm	Plankton 10-50 µm	Total Bacteria	Culturable Hetero-trophic Bacteria	Reference
Hyde Guardian	Shipboard	≥-2.4	-1.4	–	0.9	IMO 2009
Hyde Guardian	Land-based - 32 psu	≥-4.2	≥-1.1	-0.4	–	Veldhuis 2009; IMO 2009
Hyde Guardian	Land-based - 23 psu	≥-3.6	≥-1.2	0.1	–	Veldhuis 2009; IMO 2009
NEI	Land-based - 72 hr	-3.7	>-1	–	–	NEI 2007
NEI	Land-based - 96 hr	-4.0	>-1	–	–	NEI 2007
NEI	Land-based - 120 hr	>-4.5	>-1	–	–	NEI 2007
NEI	Land-based - 168 hr	>-4.0	>-2	–	–	NEI 2007
NEI	Land-based - freshwater 96 hr	>-4.8	>-2	–	–	NEI 2007
NEI	Land-based - *Artemia* 24 hr	-1.9	–	–	–	NEI 2007
NEI	Land-based - *Artemia* 48 hr	>-4.9	–	–	–	NEI 2007
NEI	Shipboard	≥-4.0	>-1	–	–	NEI 2007
SEDNA Peraclean	Land-based - high salinity	-4.7	>-3.5	0.5	≥2.8	Veldhuis & Fuhr 2008
SEDNA Peraclean	Land-based - low salinity	-4.9	>-3.8	0.3	1.4	Veldhuis & Fuhr 2008
SEDNA Peraclean	Shipboard	-3.4	>-3.6	0.0	<-2.7	Gollasch & Veldhuis 2008

Appendix 2. Cost Estimate Adjustments and Calculation of Annualized Costs

Estimates made in foreign currencies in the original publications were converted into US dollars at the daily average interbank transfer rates reported at http://www.oanda.com/currency/historical-rates on the date of publication or presentation, or on the first day of the month where only the month of publication was given. For the estimates used in this report, the transfer rates are listed in Table A2-1.

Table A2-1. Currency exchange rates used in this report.

Publication	Original Currency	Exchange Date	US Exchange Rate
Pollutech 1992	Canadian dollars	3/31/1992	0.845700
AQIS 1993	Australian dollars	6/1/1993	0.676000
Ogilvie 1995	New Zealand dollars	6/29/1995	0.762266
Aquatic Sciences 1996	Canadian dollars	8/1/1996	0.728000
Victoria ENRC 1997	Australian dollars	10/1/1997	0.727800

Estimates were inflated from the date of original publication, or from the first day of the month where only the month of publication was given, to June 1, 2010 using the calculator at http://inflationdata.com/inflation/Inflation_Calculators/InflationCalculator.asp, which is based on the U.S. Bureau of Labor Statistics' Consumer Price Index for all Urban Consumers (CPI-U).

Total annualized costs were calculated as the sum of the annual operations & maintenance (O&M) costs and the annualized capital costs:

$$A_T = A_{O\&M} + A_C$$

with:

$$A_C = iC/(1-(1+i)^{-N})$$

where i = the annual interest rate on borrowed capital, C = the capital cost, and N = the working lifetime of the plant or equipment in years. This formula assumes that the entire capital cost is incurred at the start of the project. We assumed an interest rate of 5%, and the following working lifetimes:

New cargo vessel	25 years
Retrofitted cargo vessel	12.5 years
Treatment ship	20 years
On-land treatment plant	30 years

Appendix 3. Adjustment of the Cost Estimates in Brown and Caldwell (2007) to the Design Criteria in Brown and Caldwell (2008)

The design criteria used in the two studies and the ratios between them are shown in Table A3-1. Cost estimates made on the basis of the first set of design criteria were adjusted to reflect the second set of design criteria as described below.

Table A3-1. Design criteria in Brown and Caldwell (2007) and (2008).

Design Criterion	2007 Study	2008 Study	Ratio (2008:2007)
Ballast Discharge Rate (gpm)	3,000	10,000	3.33
Storage (gallons)	500,000	2,700,000	5.40
Treatment Rate (gpm)	350	1,000	2.86

Capital cost of pipes: The cost estimate for pipes from the berths to the treatment plant reflecting the 2008 study's Ballast Discharge Rate was interpolated from the values in Table 4 in Brown and Caldwell (2007). This cost estimate is 1.7 times the estimate in Brown and Caldwell (2007) based on the 2007 study's Ballast Discharge Rate.

Capital cost for on-land storage tanks: This estimate was taken from Table 6 in Brown and Caldwell (2007) for 3 million gallons of storage (2.7 million gallons of storage is required). This cost estimate is 2.8 times the estimate in Brown and Caldwell (2007) based on the 2007 study's Storage requirement.

Capital cost for barge purchase and modification: This was estimated as the cost of two barges, since one barge has a storage capacity of 1,700,000 gallons (Brown and Caldwell 2007 at p. 15) and 2,700,000 gallons of storage is needed. This value is thus double the estimate in Brown and Caldwell (2007) based on the 2007 study's Storage requirement.

Capital cost for collection pumps: The governing criterion is the Ballast Discharge Rate, which is 3.33 times higher in the 2008 study than in the 2007 study. Other capital costs show substantial economies of scale, that is, the ratio of estimated costs is less than the ratio of design criteria (Table A3-2). To reflect economies of scale, the estimated cost for collection pumps was increased by 1.7 relative to the estimate in Brown and Caldwell (2007), which is based on the 2007 study's Ballast Discharge Rate.

Table A3-2. Comparison of criteria and cost estimate ratios for pipe, storage and barge estimates.

Estimated Cost	Governing Criterion	Ratio of Criteria	Ratio of Cost Estimates
Pipes	Ballast Discharge Rate	3.33	1.7
Storage Tanks	Storage	5.40	2.8
Barge	Storage	5.40	2.0

Capital cost for lift station: The governing criterion is the Treatment Rate, which is 2.86 times higher in the 2008 study than in the 2007 study. As with the estimated capital cost for collection pumps, in order to reflect economies of scale the estimated cost for the lift station was increased by 1.7 relative to the estimate in Brown and Caldwell (2007) based on the 2007 study's Treatment Rate.

Capital costs for treatment systems: For Filtration & UV, Ozonation, and Membrane Filtration, the governing criterion is the Treatment Rate, which is 2.86 times higher in the 2008 study than in the 2007 study. For these systems, as with other capital costs whose size is governed by flow rates, in order to reflect economies of scale the estimated cost was increased by 1.7 relative to the estimates in Brown and Caldwell (2007) based on the 2007 study's Treatment Rate.

For Hydrodynamic Cavitation, part of the capital cost is to provide additional storage. This part of the cost was estimated from Table 6 in Brown and Caldwell (2007) for 3 million gallons of storage (2.7 million gallons of storage is required). For the remaining part of the capital cost, as with other capital costs whose size is governed by flow rates, in order to reflect economies of scale the estimated cost was increased by 1.7 relative to the estimates in Brown and Caldwell (2007) based on the 2007 study's Treatment Rate.

Barge O&M: These costs are for towing services, which are based on the number of ship arrivals per year. This number did not change between the two studies, so this cost estimate was not changed.

Treatment system O&M: These costs, and equipment replacement costs which are here included under O&M, appear to be based on the total annual volume of ballast water discharged. This does not appear to change between the two studies, so this cost estimate was not changed.

Two sensitivity analyses were conducted to assess the above assumptions. If the capital costs for collection pumps, lift stations and treatment systems are increased proportional to the governing criteria (Ballast Discharge Rate or Treatment Rate) rather than by a factor of 1.7 (i.e. if we assume that there are no economies of scale in the capital costs for these system components), the cost estimates for the various systems increase by 9-19%. If Treatment system O&M costs are increased proportional to the governing criterion (Treatment Rate) rather than not increased, the cost estimates for the various systems increase by 3-6%. The adjustments in the cost estimates thus seem fairly robust relative to these assumptions.

Appendix 4. Estimates of Treatment Plants and Capacities in Onshore and Shipboard Treatment Approaches for Milwaukee, Australia, California and the United States

Shipboard ballast water treatment systems must generally be sized large enough to accommodate the maximum ballast pumping capacities of the ships they are installed on (Table A4-1). This requires some very large-capacity treatment plants—in the largest vessels, the required 20,000 MT/h capacity is greater than the estimated wastewater treatment capacity needed to serve the population of Phoenix, Arizona, the fifth largest city in the United States (Table A4-2). In contrast, onshore ballast treatment plants with adequate storage need only be large enough to treat at the average (not the maximum) ballast discharge rate. This results in a large difference in the required treatment capacity in shipboard and onshore approaches.

Table A4-1. Ships' total ballast pump capacities. The total ballast pump capacity is the summed capacities of all ballast pumps that can operate simultaneously.

Vessel Type	Typical Total Ballast Pump Capacity (MT/h)	Reference
Containerships	250-750	ABS 2010
Australian Containerships	500-2,000	AQIS 1993a
Containerships	1,100	Rigby & Taylor 2001b
Containerships	1,000-2,000	NRC 1996
Japan-Oregon Woodchip Carriers	780-975	Carlton et al. 1995
Australian Woodchip Carriers	1,000-1,500	AQIS 1993a
Bulk Carriers	1,300-3,000	ABS 2010
Australian Bulk Carriers	1,000-6,000	AQIS 1993a
Capesize Bulk Carriers	6,000	Rigby & Taylor 2001b
Bulk Carriers	2,000-10,000	Reeves 1999
Bulk Carriers, Ore Carriers	5,000-10,000	NRC 1996
Largest Bulk Carriers	to >20,000	AQIS 199a
Australian Tankers	750-3,000	AQIS 1993a
Tankers	1,100-5,800	ABS 2010
LNG Tanker	6,000	Rigby & Taylor 2001b
Tankers	5,000-20,000	NRC 1996; Reeves 1999
Largest Tankers	to >20,000	AQIS 199a
New Zealand ships	1,000-1,500	Ogilvie 1999
Great Lakes ships	550-3,500	Brown and Caldwell 2008

Great Lakes ships	400-5,000	Pollutech 1992
Great Lakes ships	2,000-5,900	Aquatic Sciences 1996
Largest vessels	15,000-20,000	NRC 1996

Table A4-2. Estimated wastewater treatment capacities needed to serve the populations of selected US cities. Based on July 1, 2008 populations (U.S. Census 2010) and the average per capita domestic wastewater production in North America (UNEP 2000). Rank is the rank among U.S. cities in population.

Treatment Capacity (MT/h)	City	Population	Rank
16,987	Phoenix AZ	1,568,000	5
4,897	Kansas City MO	452,000	39
4,702	Cleveland OH	434,000	41
4,474	Miami FL	413,000	43
1,972	Salt Lake City UT	182,000	125
1,495	Syracuse NY	138,000	174
1,387	Cedar Rapids IA	128,000	187
1,343	Hartford CT	124,000	193

The treatment plant and treatment capacity needed for onshore treatment in the Port of Milwaukee, Australia and California were estimated based on conceptual design studies of onshore treatment in those locations (with various adjustments described below). The estimate for the U.S. was based on the California estimate adjusted to reflect the larger amount of ballast water that is discharged in the U.S. The shipboard treatment estimates were based on the estimated number of distinct ships arriving or discharging ballast in these locations (for the number of treatment plants), multiplied by the average ballast pump capacity of these ships (for the treatment capacity). For sites with onshore studies that include on-land treatment plants, the project period for the estimate is 30 years based on the estimated useful life of an on-land treatment plant (Appendix 2). For the onshore study based on a treatment ship only (Brown and Caldwell 2008), the project period for the estimate is 20 years. For each site, the estimated number of affected ships for the shipboard estimate was based on these project periods, adjusted to reflect the estimated 25-year useful life of a ship.

In each of these estimates, adjustments were selected that are *conservative* in the sense of tending to produce a smaller shipboard:onshore ratio for treatment plants or treatment capacity, which is the sense in which the word is used below. That is, as used in this Appendix, conservative adjustments are those that tend to raise the number of treatment plants or the total treatment capacity needed for onshore treatment, or to lower those numbers for shipboard treatment.

<u>Port of Milwaukee (overseas ships only)</u>

Onshore estimate: Brown and Caldwell (2008) estimated that a single ballast water treatment ship with a maximum treatment rate of 230 MT/h could serve the overseas ships calling at the Port of Milwaukee.

Shipboard estimate, number of treatment plants: About 85 overseas ships call at the port each year during the 8 months that the St. Lawrence Seaway is open (Brown and Caldwell 2008). Assuming that each roundtrip voyage takes a month, this would require a minimum of 11 different overseas cargo ships to visit the port during the first year. Over the remaining 19 years of the 20-year period of the estimate (corresponding to the estimated useful working life a treatment ship), other overseas cargo ships would call at the Port consisting of a combination of (a) new ships that come into service to replace ships that had called at the Port during the first year, and (b) other ships, including other new ships and old ships that hadn't called at the Port during the first year. With a typical useful working life for a cargo ship of 25 years, approximately 19/25 of the ships calling at the Port in the first year will go out of service and be replaced by other vessels during the remainder of the 20-year period. Since raising the number of ships raises the number of treatment plants and the total treatment capacity that would need to be installed to accommodate shipboard treatment, we conservatively adjust the number of ships by counting only the additional ships that call as replacements for the ships that called during the first year, and ignoring other ships. The estimated number of distinct ships, and of treatment plants needed, is thus 19 (= 11 x (1 + 19/25)).

Shipboard estimate, treatment capacity: In describing ships at the Port of Milwaukee, Brown and Caldwell (2008) state that "typically, cargo ships have two to three pumps that pump the ballast water to one of the various discharge locations on the ship...In general, each of the pumps within the ballast water tanks has a capacity that ranges from 1,000 gpm to 5,000 gpm, and often two of the pumps operate simultaneously." Thus, these ships typically have ballast pump capacities of 2,000 gpm (≈450 MT/h) to 10,000-15,000 gpm (≈2,300-3,400 MT/h). For the estimate, we assumed an average capacity of 1,200 MT/h. With 19 distinct ships, the total treatment capacity that will need to be installed is 22,800 MT/h.

<u>Australia</u>

Onshore estimate: AQIS (1993a) estimated that Australia's domestic and foreign ballast discharges could be treated with 3 treatment ships and 18 on-land treatment plants located in Australia's major ports, along with 16 barges to transport ballast water collected at smaller ports. Since the estimated working lives are 20 years for a treatment ship and 30 years for an on-land plant, a 30-year period was used for the estimate and the number of treatment ships required was increased to 5. This is a conservative adjustment, since the calculated need over 30 years is for only 4.5 treatment ships. The total treatment capacity of the 18 on-land plants and 5 treatment ships is 34,940 MT/h.

Shipboard estimate: AQIS (1993a, pp. 86, 88) reported that at least 1,000 different ships visit Australian ports each year, discharging 66 million MT of ballast water. If each of these ships discharges its entire typical ballast load into Australian waters once a month, the typical ballast load would be 5,500 MT. Data on Australian ships shows that ballast pump capacities are about 10% of typical ballast loads (AQIS 1993a, Table 4.1), thus the average ballast pump capacity for Australian vessels is estimated to be 550 MT/h. This is almost certainly a substantially conservative estimate, since AQIS (1993a, Table 4.1) lists typical ballast pump capacities for ships in Australia ranging from 500 MT/h (for small containerships) to 6,000 MT/h (for large bulk carriers), with an unweighted average for different ship types of 2,089 MT/h. Using a higher estimate of average ballast pump capacity would produce a correspondingly higher estimate of the total treatment capacity needed.

Adjusting the ship numbers to a 30-year period by adding only the expected number of replacement ships (and ignoring other ships, a conservative adjustment) yields 2,160 distinct ships requiring 2,160 treatment plants. With an average ballast pump capacity of 550 MT/h, a total treatment capacity of over one million MT/h would need to be installed.

<u>California</u>

Onshore estimate: CAPA (2000) estimated that 10 on-land treatment plants (one at each of ten ports) with a total treatment capacity of 489 MT/h could treat the ballast water discharged into California waters. However, the port descriptions in this study suggested that it would be more economically efficient to serve some of the ports with a few smaller treatment plants rather than a single larger one, so we instead estimated that a total of 16 onshore plants are needed.

The conceptual design in CAPA (2000) provided sufficient storage at each site to allow the plants to treat the ballast water at the average rate of discharge. However, the study developed designs and cost estimates for only a few sizes of treatment plant, and allocated to each port the next size of plant that was greater than the average ballast discharge at that port. In some cases these plants were nearly 50% larger than needed, resulting in an estimate of total treatment capacity needed in the state (489 MT/h) that is nearly 30% higher than the average rate of discharge in the state (377 MT/h). We conservatively based our estimate on the inflated estimate used in the CAPA (2000) report.

The estimates in CAPA (2000) were based on some of the earliest ballast discharge data collected by the U.S. Coast Guard or the State of California, which covered less than a year at the time of the study, only included data from ships that had traveled overseas, and suffered from low reporting rates. CAPA (2000) corrected for the time period (that is, annualized the data) but not for the other data limitations. We utilized the most recent available report from the National Ballast Information Clearinghouse summarizing U.S. Coast Guard ballast water data (Miller et al. 2007, covering data for 2004-2005), adjusted these data for reporting rates aggregated by Captain of the Port Zones (COPTZ) in California, and summed these for both foreign and domestic ballast water to estimate total ballast discharge in California (Table A4-3). We then adjusted the treatment capacity estimate from CAPA (2000) by the ratio between the estimate that we derived for California discharge from the Miller et al. (2007) data (12,251,089 MT/y, see table below) and the CAPA (2000) estimate for California discharge (3,302,988 MT/y, summed from Table 5.2 in CAPA (2000)), yielding an estimate of 1,814 MT/h of onshore treatment capacity needed in California (or nearly 4 times the estimate in CAPA (2000)).

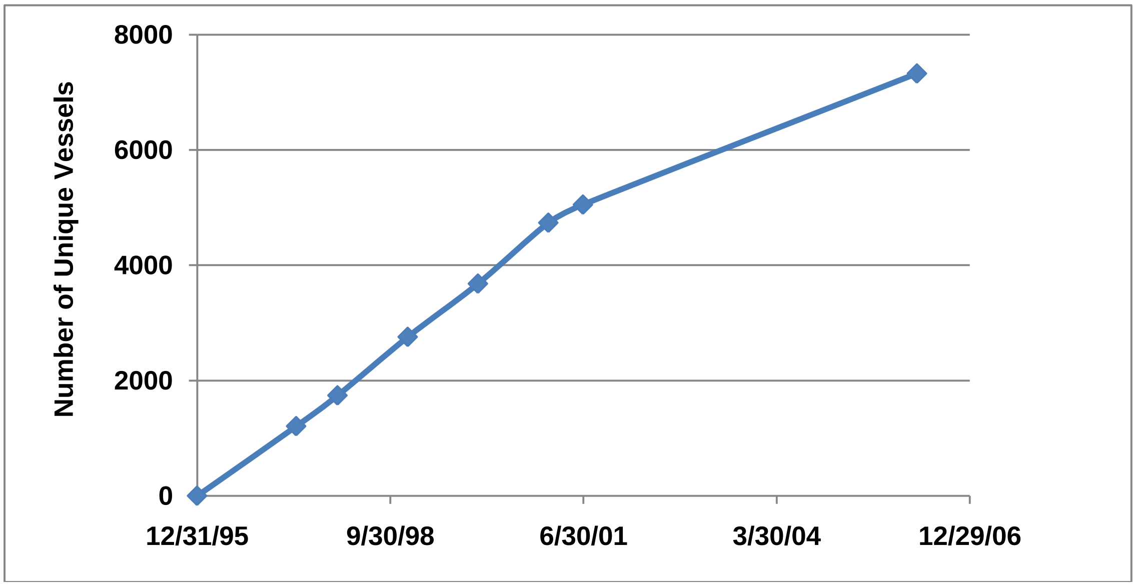
Table A4-3. Estimate of the total annual ballast water discharge into California waters (metric tons).

		Domestic			**Foreign**		**Total**
	Reported Discharge	Reporting Rate	Estimated Discharge	Reported Discharge	Reporting Rate	Estimated Discharge	Estimated Discharge
Source:	Table 8	Table 4		Table 6	Table 3		
DATA FOR 2004-2005							
SFCMS	4,379,050	104.8	4,178,483	2,975,652	73.7	4,037,520	8,216,003
LOSMS	4,612,242	78.6	5,867,992	5,741,283	98.4	5,834,637	11,702,629
SDCMS	3,452,378	77.7	4,443,215	112,825	80.4	140,330	4,583,545
California			14,489,690			10,012,487	24,502,177
ANNUAL DATA							
California			7,244,845			5,006,244	12,251,089

Source is the table in Miller et al. 2007 from which the data were taken. Captain of the Port Zones are: SFCMS = San Francisco; LOSMS = Los Angeles-Long Beach; SDCMS = San Diego

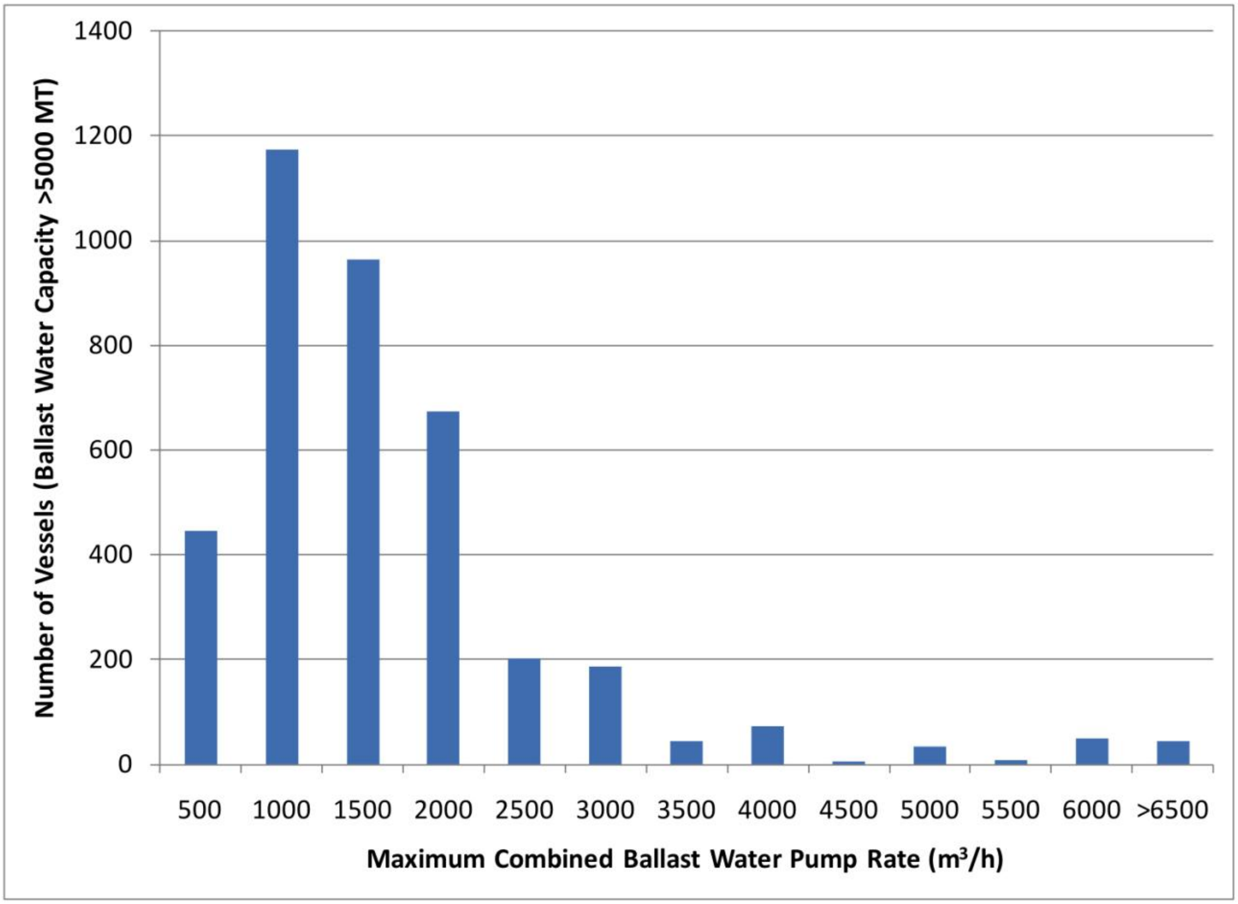
Shipboard estimate, number of treatment plants: Figure A4-1 below shows the estimated cumulative number of distinct ships arriving at California ports since January 1, 2000, based on data provided by the California State Lands Commission or contained in California SLC (2010). It's not clear whether the data for the first 4.5 years includes ships on coastal voyages, since such ships were not required to file ballast water report forms during that time; if these are not included, Figure A4-1 could substantially underestimate the number of distinct ships. A total of 7,327 distinct ships were recorded through March 31, 2010, a period of 10.25 years. Adjusting the ship numbers for the 30-year period by adding only the expected number of replacement ships (a conservative adjustment) yields 13,115 distinct ships expected to be subject to ballast water regulations, potentially requiring 13,115 treatment plants. However, not all arriving ships discharge ballast water, so it's not clear whether all of these ships would need a treatment plant installed. This is discussed further below under the estimate of shipboard treatment capacity.

Figure A4-1. Cumulative number of unique ships arriving at California ports since January 1, 2000. Includes a small number of unmanned barges (a total of 28 through June 2005).



Shipboard estimate, treatment capacity: Figure A4-2 shows California State Lands Commission data on the ballast pump capacities in a sample of nearly 4,000 distinct ships arriving in California ports. The average ballast pump capacity estimated from this figure is 1,436 MT/h. With 13,115 distinct ships, this yields an estimate of nearly 19 million MT/h of treatment capacity that would need to be installed.

Figure A4-2. Total ballast pump capacities of ships that call at California ports. Source: California SLC 2010, Fig. VI-3.



As mentioned, not all vessels discharge ballast water on arriving at a California port, so not all of the distinct arriving ships may need to install treatment plants. Thus these numbers might overestimate, perhaps substantially, the number of plants and the treatment capacity needed for shipboard treatment. How significant could this overestimation be? On average, only 20% of ship arrivals at California ports report discharging ballast water (California SLC 2010); however, there is no independent verification of whether ships have or have not discharged ballast water, and there are reasons to suspect that ships often fail to report some of their discharges. Glosten (2002) reported that they "were often told by agents and operators that their vessels never discharge ballast in Puget Sound. However, we found that almost every vessel surveyed discharged ballast at some point while they were in port, usually for trim and list control, while loading and off-loading cargo." Glosten (2002) concluded that the under-reporting occurred because many ship operators mistakenly excluded such common practices from their definition of ballast discharge. However, there is also a financial incentive for ship operators to not report ballast discharges: a ship reporting that it intends to discharge ballast is more likely to have its ballast tanks sampled, which is an inconvenience that involves some risk of delay, and which at least theoretically increases the chance that it will be found to be out of compliance and subjected to penalties. Studies in Australia (Lockwood 1999), the Great Lakes (Reeves 1998) and Washington (Harkless 2003; Lyles 2004) found evidence that ships routinely misreported their ballast management activities (see also Cohen & Foster 2000 at footnote 163). Harkless (2003) reported that some Chief Mates admitted that they intentionally reported false ballast water information in order to satisfy regulators.

Even if the figure of ballast discharge by only 20% of California ship arrivals is accurate, much more than 20% of the individual ships would probably need to install treatment plants to treat the ballast discharged on *some* voyages. For example, if each ship discharged ballast on half of its arrivals at California ports, then 100% of ships would need to treat ballast water even though only 50% of arrivals involved ballast discharges. As a sensitivity test, we recalculated the treatment plant and capacity estimates for California assuming the most extreme hypothetical case of only 20% of arriving ships ever discharging ballast water in the state (Table A4-4; compare to Table VI.B-2). In this case the number of treatment plants needed for shipboard treatment is 164 times the number needed for onshore treatment (down from 820 in Table VI.B-2) and the treatment capacity needed is 2,076 times the need with onshore treatment (down from 10,382 in Table VI.B-2). Though less, the difference is still striking.

Table A4-4. Treatment plant and capacity estimates for the California, assuming that only 20% of ships arriving in California ever discharge ballast water there.

	Number of Treatment Plants		Total Capacity of Treatment Plants (MT/h)	
Site	**Onshore**	**Shipboard**	**Onshore**	**Shipboard**
California	16	2,623	1,814	3,766,628

United States

Onshore estimate: To estimate the number of onshore treatment plants and the treatment capacity needed in the United States, we started with the estimates for California derived above. We then multiplied these by the ratio between the estimated total ballast water discharge in the United States (239,989,668 MT/y derived from Miller et al. 2007 by the methods described earlier, see Table A4-5) and the estimated discharge in California (12,251,089 MT/y). This yielded an estimate of 314 onshore treatment plants needed with a total treatment capacity of 35,549 MT/h.

Table A4-5. Estimate of the total annual ballast water discharge into U.S. waters, compared to the estimate for California.

	Domestic			Foreign			Total
	Reported Discharge	Reporting Rate	Estimated Discharge	Reported Discharge	Reporting Rate	Estimated Discharge	Estimated Discharge
US 2004-05	183,792,889	48.9	375,854,579	73,720,328	70.8	104,124,757	479,979,336
US annual	–	–	187,927,290	–	–	52,062,379	239,989,668
CA annual	–	–	7,244,845	–	–	5,006,244	12,251,089

Shipboard estimate: Approximately 40,000 cargo ships (excluding barges) are estimated to be subject to ballast water discharge requirements in the United States over the three-year VGP period (Albert & Everett 2010; (Ryan Albert, pers. comm., SAB public conference call 10/26/2010). Adjusting the ship numbers for a 30-year period by adding only the expected number of replacement ships (a conservative adjustment) and assuming an average 25-year lifetime for a ship yields 83,200 distinct ships requiring 83,200 treatment plants. No data on ballast pump capacities comparable to the California data in Figure 2 are available for the U.S. as whole. We used California's average ballast pump capacity of 1,436 MT/h, to yield an estimate of total treatment capacity of 119 million MT/h need for shipboard treatment.

Appendix 5. Cost Analysis

This appendix shows the source data and explains the calculations of the cost comparison in §VI.E "Cost of Onshore vs. Shipboard Treatment". The assumptions and some common data used in these calculations are in Table A5-1. The inflation figures are based on the U.S. Bureau of Labor Statistics' Consumer Price Index for all Urban Consumers (CPI-U), as described in Appendix 2.

Table A5-1. Assumptions and some common data for the cost analysis.

0.05	Annual interest rate
30	Lifetime of onshore components (years)
25	Lifetime of new ship outfitted at the time of construction with treatment plants or with pipes and pumps to discharge ballast water onshore; shipboard plant, pipes and pumps assumed to have the same lifetime as the ship (years)
12.5	Remaining lifetime of old ships retrofitted with treatment plants or with pipes and pumps to discharge ballast water onshore; shipboard plant, pipes and pumps assumed to have the same lifetime as the ship (years)
1.2548	Inflation from 9/1/2000 to 6/1/2010 (from publication of CAPA 2000 to present)
1.2307	Inflation from 1/1/2002 to 6/1/2010 (from publication of Glosten 2002 to present)
0.9949	Inflation from 8/1/2008 to 6/1/2010 (from publication of Brown and Caldwell 2008 to present)
1.0056	Inflation from 2/1/2010 to 6/1/2010 (from publication of Lloyd's Register 2010 to present)
3,302,988	Total California ballast water discharge, as reported in CAPA 2000 (MT/y)
12,251,089	Total California ballast water discharge based on the most recent NBIC report, Miller et al. 2007 (covering 2004-05), foreign & domestic combined, adjusted for reporting rates (MT/y)
239,989,668	Total U.S. ballast water discharge based on the most recent NBIC report, Miller et al. 2007 (covering 2004-05), foreign & domestic combined, adjusted for reporting rates (MT/y)
3.7	Ratio of the California ballast water discharge estimate based on Miller et al. 2007 to the estimate in CAPA 2000
19.6	Ratio of the U.S. to the California ballast water discharge estimates based on Miller et al. 2007

California - Onshore Cost - (1) On-land Component

The original cost data from CAPA (2000) is shown in Table A5-2. Under Annualized Costs, the first column shows the figures from CAPA (2000) and the second column shows annualized costs calculated by the method described inn Appendix 2.

Table A5-2. Costs for onshore treatment in California from CAPA (2000), Tables 5.1 and 5.2.

Port	Capital Costs				Annual O&M	Annualized Costs	
	Pipes	Storage Tanks	Treatment Plants	Outfalls		CAPA	Calculated
Hueneme	1,056,000	55,000	0	100,000	0	40,367	78,777
Humboldt Bay	12,672,000	4,000,000	1,781,000	100,000	149,800	768,233	1,356,699
Long Beach	28,617,600	5,100,000	2,220,400	100,000	223,454	1,424,721	2,567,778
Los Angeles	27,033,600	20,400,000	2,220,400	100,000	223,454	1,881,921	3,460,023
Oakland	15,840,000	3,800,000	1,781,000	100,000	149,800	867,167	1,549,772
Redwood City	1,584,000	4,300,000	1,631,500	100,000	142,400	396,250	637,799
Richmond	5,808,000	3,400,000	1,631,500	100,000	142,400	507,050	854,030
Sacramento	1,372,800	4,800,000	1,631,500	100,000	142,400	405,877	656,586
San Diego	9,292,800	3,100,000	1,631,500	100,000	142,400	613,210	1,061,206
San Francisco	8,448,000	6,300,000	1,781,000	100,000	149,800	704,100	1,231,540
Stockton	5,385,600	5,500,000	1,631,500	100,000	142,400	562,970	963,160
Calif. Total	117,110,400	60,755,000	17,941,300	1,100,000	1,608,308	8,171,865	14,417,371

Table A5-3 shows the costs from Table A5-2, not including the CAPA (2000) figures for annualized costs, adjusted for inflation.

Table A5-3. Costs for onshore treatment in California from CAPA (2000), adjusted for inflation.

Port	Capital Costs				Annual O&M	Annualized Costs
	Pipes	Storage Tanks	Treatment Plants	Outfalls		
Hueneme	1,325,069	69,014	0	125,480	0	98,850
Humboldt Bay	15,900,826	5,019,200	2,234,799	125,480	187,969	1,702,386
Long Beach	35,909,364	6,399,480	2,786,158	125,480	280,390	3,222,047
Los Angeles	33,921,761	25,597,920	2,786,158	125,480	280,390	4,341,637
Oakland	19,876,032	4,768,240	2,234,799	125,480	187,969	1,944,654
Redwood City	1,987,603	5,395,640	2,047,206	125,480	178,684	800,310
Richmond	7,287,878	4,266,320	2,047,206	125,480	178,684	1,071,637
Sacramento	1,722,589	6,023,040	2,047,206	125,480	178,684	823,884
San Diego	11,660,605	3,889,880	2,047,206	125,480	178,684	1,331,601
San Francisco	10,600,550	7,905,240	2,234,799	125,480	187,969	1,545,337
Stockton	6,757,851	6,901,400	2,047,206	125,480	178,684	1,208,574
Calif. Total	146,950,130	76,235,374	22,512,743	1,380,280	2,018,105	18,090,918

Table A5-4 shows the costs from Table A5-3, with various adjustments to correspond to a 3.7x higher estimate of ballast water discharge than was used in CAPA (2000). These include the following:

• *Pipe Capital Costs*: Costs from Table A5-3 were adjusted by (1) multiplying the maximum discharge/day for each port (from CAPA 2000, Table 4.4) by 3.7; (2) selecting the least-cost set of pipe sizes from Brown and Caldwell (2007, Table 4) that are capable of handling the adjusted maximum discharge/day, expressed as gallons per minute (gpm); (3) multiplying the construction cost per lineal foot (Brown and Caldwell 2007, Table 4) times the total length of pipe needed at that port (CAPA 2000, Table 4.2); adding 25% for contingency and 30% for technical services; and inflating to June 1, 2010 dollars. The details of the pipe calculations are shown below in Table A5-5.

• *Storage Tank and Outfall Capital Costs, and Annual O&M*: Costs from Table A5-3 were multiplied by 3.7. This may be an overestimate (especially for capital costs) because it fails to account for economies of scale.

• *Treatment Plant Capital Cost*s: Costs from Table A5-3 were adjusted by multiplying the required treatment capacity for each port (CAPA 2000: Table 4.5) by the ratio between our best estimate of California BW discharge and CAPA's estimate, selecting the least-cost set of treatment plant sizes from CAPA 2000: Table 4.7 that can handle the adjusted required treatment capacity, and inflating to June 1, 2010 dollars. Includes 30% contingency. This is probably an overestimate because it fails to account for economies of scale in the larger plants. The details of the pipe calculations are shown below in Table A5-6.

Table A5-4. Costs for onshore treatment in California from CAPA (2000), adjusted for inflation and to an updated estimate for California ballast water discharge.

Port	Capital Costs				Annual O&M	Annualized Costs
	Pipes	Storage Tanks	Treatment Plants	Outfalls		
Hueneme	1,245,877	255,979	0	465,417	0	127,974
Humboldt Bay	34,350,611	18,616,679	2,786,158	465,417	697,195	4,354,312
Long Beach	77,600,343	23,736,265	8,358,474	465,417	1,039,993	8,206,091
Los Angeles	238,318,485	94,945,061	11,144,632	465,417	1,039,993	23,474,515
Oakland	42,893,768	17,685,845	2,786,158	465,417	697,195	4,849,505
Redwood City	3,737,631	20,012,929	2,786,158	465,417	662,754	2,419,281
Richmond	15,840,437	15,824,177	2,234,799	465,417	662,754	2,898,235
Sacramento	3,737,631	22,340,014	2,786,158	465,417	662,754	2,570,662
San Diego	20,534,724	14,427,926	2,786,158	465,417	662,754	3,148,644
San Francisco	22,959,735	29,321,269	2,786,158	465,417	697,195	4,309,669
Stockton	14,594,560	25,597,933	2,234,799	465,417	662,754	3,452,986
Calif. Total	475,813,801	282,764,077	40,689,651	5,119,587	7,485,338	59,811,874

Table A5-5. Estimate of Pipe Capital Costs for onshore treatment in California. CAPA Maximum Discharge is from CAPA (2000), Table 4.4. Adjusted Maximum Discharge is CAPA Maximum Discharge multiplied by 3.7 and expressed as gpm. Pipe Capacity and Pipe Diameter are the pipe sizes from Brown and Caldwell (2007), Table 4 needed to handle the Adjusted Maximum Discharge (3 of the available sizes of pipes are need for the Port of Los Angeles), and Unit Construction Cost is from the same table. Pipe Length is from CAPA (2000), Table 5.1. Total Capital Cost is Unit Construction Cost times Pipe Length, adjusted for inflation.

Port	CAPA Maximum Discharge (gpd)	Adjusted Maximum Discharge (gpm)	Pipe Capacity (gpm)	Pipe Diameter (in)	Unit Construction Cost (lineal foot)	Pipe Length (km)	Total Capital Cost
Hueneme	54,128	139	1,000	10	140	1.6	1,245,877
Humboldt Bay	3,944,058	10,159	16,667	36	320	19.3	34,350,611
Long Beach	5,104,821	13,149	16,667	36	320	43.6	77,600,343
Los Angeles #1			25,000	42	440		
Los Angeles #2	20,285,271	52,250	25,000	42	440	41.2	238,318,485
Los Angeles #3			3,000	16	160		
Oakland	3,667,472	9,447	16,667	36	320	24	42,893,768
Redwood City	4,181,547	10,771	16,667	36	320	2	3,737,631
Richmond	3,312,692	8,533	16,667	36	320	9	15,840,437
Sacramento	4,711,895	12,137	16,667	36	320	2	3,737,631
San Diego	3,016,584	7,770	8,333	30	260	14	20,534,724
San Francisco	6,202,051	15,975	16,667	36	320	13	22,959,735
Stockton	5,469,666	14,089	16,667	36	320	8	14,594,560
Calif. Total	59,950,185	154,417	195,669	–	–	178	475,813,801

Table A5-6. Estimate of Treatment Plant Capital Costs for onshore treatment in California. CAPA Required Treatment Capacity is from CAPA (2000), Table 4.5. Adjusted Required Treatment Capacity is CAPA Required Treatment Capacity multiplied by 3.7. Treatment Plant Size is the minimum plant size as a multiple of the plant sizes whose costs were estimated in CAPA (2000) (0.1, 0.2 and 1.0 mgd), and Plant Cost is the cost estimated as multiples of the CAPA (2000) plant costs (i.e. the cost of a 3 mgd plant is estimated as 3 times CAPA's cost estimate for a 1 mgd plant), adjusted for inflation.

Port	CAPA Required Treatment Capacity (gpd)	Adjusted Required Treatment Capacity (gpd)	Treatment Plant Size (mgd)	Plant Cost
Hueneme	497	1,843	–	–
Humboldt Bay	140,084	519,585	1	2,786,158
Long Beach	679,714	2,521,122	3	8,358,474
Los Angeles	993,539	3,685,128	4	11,144,632
Oakland	159,694	592,320	1	2,786,158
Redwood City	56,493	209,538	1	2,786,158
Richmond	44,269	164,198	0.2	2,234,799
Sacramento	99,306	368,335	1	2,786,158
San Diego	56,986	211,366	1	2,786,158
San Francisco	109,124	404,751	1	2,786,158
Stockton	50,843	188,581	0.2	2,234,799
California Total	2,390,549	8,866,768	13.4	40,689,651

The area needed for storage tanks was estimated as shown in Table A5-7, and the area needed for treatment plants was estimated as 0.25 acres for a 0.2 mgd plant, and 1 acre/mgd for plants ≥1 mgd. Land Costs were estimated as shown in Table A5-8, with supporting data shown in Table A5-9. Land costs were added to the Storage and Treatment Plant capital costs in Table A5-4 to produce Table A5-10.

Table A5-7. Estimate of land needed for storage tanks for onshore treatment in California. CAPA Storage Needed is from CAPA (2000), Table 4.5. Adjusted Storage Needed is CAPA Storage Needed multiplied by 3.7. Number of Tanks is the minimum number of steel tanks of 7.3 m height and 60 m maximum diameter needed to provide the Adjusted Storage Needed. Tank Diameter gives the corresponding tank diameters. Tank Area is the area needed if each tank occupies a square with a 1 m buffer (i.e. a square whose sides equal the tank diameter plus 2 m).

Port	CAPA Storage Needed (gal)	Adjusted Storage Needed (gal)	Number of Tanks	Tank Diameter (m)	Tank Area (acres)
Hueneme	108,257	401,535	1	16.3	0.08
Humboldt Bay	7,888,116	29,257,755	6	56.7	5.1
Long Beach	10,209,642	37,868,510	7	59.8	6.6
Los Angeles	40,570,700	150,480,492	28	59.6	26.2
Oakland	7,334,944	27,205,989	5	59.9	4.7
Redwood City	8,363,094	31,019,491	6	58.4	5.4
Richmond	6,625,384	24,574,163	5	57.0	4.3
Sacramento	9,423,472	34,952,533	7	57.4	6.1
San Diego	6,033,114	22,377,381	5	54.4	3.9
San Francisco	12,403,838	46,006,987	9	58.1	8.0
Stockton	10,939,280	40,574,804	8	57.9	7.1
California Total	119,899,842	444,719,639	87	–	77.6

Table A5-8. Estimate of land costs for onshore treatment in California. Per acre land costs were estimated from the records in Table A5-9.

Port	Storage Tank Area (acres)	Treatment Plant Area (acres)	Land Cost per acre	Land Cost - Storage	Land Cost-Treatment
Hueneme	0.08	–	500,000	41,295	0
Humboldt Bay	5.1	1	700,000	3,580,950	700,000
Long Beach	6.6	3	1,000,000	6,598,423	3,000,000
Los Angeles	26.2	4	2,000,000	52,452,334	8,000,000
Oakland	4.7	1	700,000	3,317,746	700,000
Redwood City	5.4	1	500,000	2,706,521	500,000
Richmond	4.3	.25	500,000	2,147,790	125,000
Sacramento	6.1	1	500,000	3,053,230	500,000
San Diego	3.9	1	1,000,000	3,924,311	1,000,000
San Francisco	8.0	1	2,000,000	16,062,874	2,000,000
Stockton	7.1	.25	100,000	708,500	25,000
California Total	77.6	13.5	–	94,593,975	16,550,000

Table A5-9. Price of vacant industrial or commercial land offered for sale near ports. From http://www.cityfeet.com, accessed 12/1/10.

Port	Acres in parcel	Price per acre	Port	Acres in parcel	Price per acre
Humboldt Bay	3	633,333	Oakland	1	795,000
Humboldt Bay	2	604,167	Oakland	2.9	1,818,182
Long Beach	5.6	1,094,643	Redwood City	1	1,475,000
Long Beach	12.4	958,237	Redwood City	0.4	547,945
Los Angeles	1.0	932,697	Richmond	1	398,000
Los Angeles	1.0	1,350,000	Sacramento	4	381,150
Los Angeles	2.0	3,750,000	San Francisco	1.5	1,503,881
Oakland	19	684,211	Stockton	3	77,746

Table A5-10. Costs for onshore treatment in California from CAPA (2000), adjusted for inflation and to an updated estimate for California ballast water discharge, including land costs.

Port	Capital Costs				Annual O&M	Annualized Costs
	Pipes	Storage Tanks	Treatment Plants	Outfalls		
Hueneme	1,245,877	297,274	0	465,417	0	130,660
Humboldt Bay	34,350,611	22,197,629	3,486,158	465,417	697,195	4,632,794
Long Beach	77,600,343	30,334,688	11,358,474	465,417	1,039,993	8,830,483
Los Angeles	238,318,485	147,397,394	19,144,632	465,417	1,039,993	27,407,026
Oakland	42,893,768	21,003,591	3,486,158	465,417	697,195	5,110,865
Redwood City	3,737,631	22,719,451	3,286,158	465,417	662,754	2,627,870
Richmond	15,840,437	17,971,967	2,359,799	465,417	662,754	3,046,083
Sacramento	3,737,631	25,393,244	3,286,158	465,417	662,754	2,801,804
San Diego	20,534,724	18,352,237	3,786,158	465,417	662,754	3,468,977
San Francisco	22,959,735	45,384,143	4,786,158	465,417	697,195	5,484,684
Stockton	14,594,560	26,306,433	2,259,799	465,417	662,754	3,500,701
Calif. Total	475,813,801	377,358,051	57,239,651	5,119,587	7,485,338	67,041,950

California - Onshore Cost - (2) Ship Retrofit/Modification

[These cost estimates need to be completed]

References Cited

[The following includes Onshore Treatment references combined with other references from the Subgroup 3 draft response to charge question 4. Thus, this reference list needs to be culled to include only the Onshore Treatment references]

ABS. 2010. Ballast Water Treatment Advisory. American Bureau of Shipping, Houston, TX.

Agusti, S. and M.C. Sánchez (2002) Cell viability in natural phytoplankton communities quantified by a membrane permeability probe. *Limnology and Oceanography* 47: 818-828.

Albert, R. and R. Everett. 2010. Capabilities of shipboard ballast water treatment technology. Presentation to EPA's Science Advisory Board, July 29, 2010.

Albert, R., R. Everett, J. Lishman, and D. Smith (2010) *Availability and Efficacy of Ballast Water Treatment Technology: Background and Issue Paper*. U.S. EPA and USCG, Washington, DC.

American Public Health Association (APHA), American Water Works Association and Water Environment Federation (2005) *Standard Methods for the Examination of Water and Wastewater*, 21st edition. APHA, Washington, DC.

American Society of Testing and Materials (ASTM) (1996a) Standard Guide for Conducting Acute Toxicity Tests Starting with Embryos of Four Species of Saltwater Bivalve Mollusks. In: *Annual Book of ASTM Standards*, Section 11, Water and Environmental Technology, Volume 11.05 (724-94). ASTM, West Conshohocken, PA.

American Society of Testing and Materials (ASTM) (1996b) Standard Guide for Conducting Acute Toxicity Tests with Echinoid Larvae. In: *Annual Book of ASTM Standards*, Section 11, Water and Environmental Technology, Volume 11.05 (E1563-95). ASTM, West Conshohocken, PA.

Anderson, A., J. Cordell, F. Dobbs, R. Herwig, and A. Rogerson (2008) *Screening of Surrogate Species for Ballast Water Treatment*. Final Report to NSF International, Ann Arbor, MI.

Anderson, A.B., B.O. Johannessen, and E. Dragsund (2004) Ballast water treatment verification protocol – DNV. In: *Proceedings of the 2nd International Ballast Water Treatment R&D Symposium*, by J.T. Matheickal and S. Raaymakers (eds.). IMO, London, UK.

AQIS. 1992. Controls on the Discharge of Ballast Water and Sediment from Ships Entering Australia from Overseas. Australian Quarantine and Inspection Service, Notice (Barrier Co-ordination) 92/2.

AQIS. 1993a. Ballast Water Treatment for the Removal of Marine Organisms. Prepared by Gutheridge, Haskins and Davey Pty Ltd. Ballast Water Research Series Report No. 1, Australian Quarantine and Inspection Service, Canberra. 106 pages.

AQIS. 1993b. Ballast Water Management Study. Prepared by Thompson Clarke Shipping Pty Ltd. Ballast Water Research Series Report No. 4, Australian Quarantine and Inspection Service, Canberra. 254 pages.

Aquatic Sciences. 1996. Examination of Aquatic Nuisance Species Introductions to the Great Lakes through Commercial Shipping Ballast Water and Assessment of Control Options Phase II. Final Report. A report for the Canadian Coast Guard. Aquatic Sciences Inc., St. Catharines, Ontario. 60 pages.

Arkes, H. and C. Blumer (1985) The psychology of sunk cost. *Organizational Behavior and Human Decision Process* 35: 124-140.

Avnimelech, Y., B.W. Troeger and L.W. Reed (1982) Mutual flocculation of algae and clay evidence and implications. *Science* 216: 63-65.

Baldino, R. (1995) *Outline of Standard Protocols for Particulate Organic Carbon (POC) Analyses*. University of Wisconsin - Madison, Madison, WI.

Barcina, I., P. Lebaron, and J. Vives-Rego (1997) Survival of allochthonous bacteria in aquatic systems: a biological approach. *FEMS Microbiology Ecology* 23: 1-9.

Bergh, O., K.Y. Børsheim, G. Bratbak, and M. Heldal (1989) High abundance of viruses found in aquatic environments. *Nature* 340: 467-468.

Binet, M.T. and J.L. Stauber (2006) Rapid flow cytometric method for the assessment of toxic dinoflagellate cyst viability. *Marine Environmental Research* 62: 247-260.

Blenkinsopp, S.A. and M.A. Lock (1990) The measurement of electron transport system activity in river biofilms. *Water Research* 24: 441-445.

Bolch, C.J. and G.M. Hallegraeff (1993) Chemical and physical treatment options to kill toxic dinofla-gellate cysts in ships' ballast water. *Journal of Marine and Environmental Engineering* 1: 23-29.

Bowles, N.D., H.W. Pearl, and J. Tucker (1985) Effective solvents and extraction periods employed in phytoplankton carotenoid and chlorophyll determination. *Canadian Journal of Fisheries and Aquatic Science* 42: 1127-1131.

Boyer, G.L. (2007) The occurrence of cyanobacterial toxins in New York lakes: Lessons from the MERHAB-Lower Great Lakes Program. *Lake and Reservoir Management* 23:153-60

Boyer, J.N., C.R. Kelbe, P.B. Ortner, and D.T. Rudnick (2009) Phytoplankton bloom status: Chlorophyll *a* biomass as an indicator of water quality condition in the southern estuaries of Florida, USA. *Ecological Indicators* 9s: s56-s67.

Brown & Caldwell. 2007. Port of Milwaukee Onshore Ballast Water Treatment–Feasibility Study Report. Prepared for the Wisconsin Department of Natural Resources. Brown and Caldwell, Milwaukee, WI. 114 pages.

Brown & Caldwell and Bay Engineering. Inc. 2008. Port of Milwaukee Onshore Ballast Water Treatment–Feasibility Study Report. Phase 2. Prepared for the Wisconsin Department of Natural Resources. Brown and Caldwell, Milwaukee, WI. 98 pages.

Brussaard, C.P.D., D. Marie, R. Thyrhaug, and G. Bratbak (2001) Flow cytometric analysis of phytoplankton viability following viral infection. *Aquatic Microbial Ecology* 26: 157-166.

Buchanan, C., R. Lacouture, H.G. Marshall, M. Olson and J. Johnson (2005) Phytoplankton reference communities for Chesapeake Bay and its tidal tributaries. *Estuaries* 28: 138-159.

Bukhari, Z., W.G. Glen, and J.L. Clancy (1999) Effects of pH on a fluorogenic vital dyes assay (4',6'-diamidino-2-phenyl-indole and propidium iodide) for *Cryptosporidium* sp. oocysts. *Water Research* 33: 3037-3039.

Burkholder, J.M. (1992) Phytoplankton and episodic suspended sediment loading: Phosphate partitioning and mechanisms for survival. *Limnology and Oceanography* 37: 974-988.

Burkholder, J.M. (1998) Implications of harmful marine microalgae and heterotrophic dinoflagellates in management of sustainable marine fisheries. *Ecological Applications* 8: S37-S62.

Burkholder, J.M. (2009) Harmful algal blooms, pp. 264-285. In: *Encyclopedia of Inland Waters, Volume 1*, by Likens GE (ed.) Elsevier, Oxford, UK.

Burkholder, J.M. and P.M. Glibert (2006) Intraspecific variability: An important consideration in forming generalizations about toxigenic algal species. *South African Journal of Marine Science* 28: 177-180.

Burkholder, J.M., A.S. Gordon, P.D. Moeller, J.M. Law, K.J. Coyne, A.J. Lewitus, J.S. Ramsdell H.G. Marshall, N.J. Deamer, S.C. Cary, J.W. Kempton, S.L. Morton, and P.A. Rublee (2005) Demonstration of toxicity to fish and to mammalian cells by *Pfiesteria* species: Comparison of assay methods and multiple strains. *Proceedings of the National Academy of Sciences (U.S.A)* 102:3471-3476.

Burkholder, J.M., G.M. Hallegraeff, G. Melia, A. Cohen, H.A. Bowers, D.W. Oldach, M.W. Parrow, M.J. Sullivan, P.V. Zimba, E.H. Allen, and M.A. Mallin (2007) Phytoplankton and bacterial assemblages in ballast water of U.S. military ships as a function of port of origin, voyage time and ocean exchange practices. *Harmful Algae* 6: 486-518.

California SLC. 2009. 2009 Assessment of the Efficacy, Availability and Environmental Impacts of Ballast Water Treatment Systems for Use in California Waters. California State Lands Commission, Sacramento, CA. 180 pages.

California SLC. 2010. Draft 2010 Assessment of the Efficacy, Availability and Environmental Impacts of Ballast Water Treatment Systems for Use in California Waters. California State Lands Commission, Sacramento, CA. 149 pages.

California SWRCB. 2002. Evaluation of Ballast Water Treatment Technology for Control of Nonindigenous Aquatic Organisms. State Water Resources Control Board, California Environmental Protection Agency, Sacramento, CA. 70 pages.

Canada. 2000. Guidelines for the Control of Ballast Water Discharge from Ships in Waters under Canadian Jurisdiction. TP 13617, Canadian Marine Advisory Council, Ottawa.

Canada. 2007. A Guide to Canada's Ballast Water Control and Management Regulations. TP 13617E, Transports Canada, Ottawa.

Cangelosi, A.A., N.L. Mays, M.D. Balcer, E.D. Reavie, D.M. Reid, R. Sturtevant, and X. Gao (2007) The response of Zooplankton and phytoplankton from the North American Great Lakes to filtration. *Harmful Algae* 6: 547-566.

CAPA. 2000. Feasibility of Onshore Ballast Water Treatment at California Ports. Prepared by URS Corporation/Dames & Moore. California Association of Port Authorities, Sacramento, CA.

Carlton, J. T., Reid, D. M. and H. van Leeuwen. 1995. Shipping Study. The Role of Shipping in the Introduction of Nonindigenous Aquatic Organisms to the Coastal Waters of the United States (other than the Great Lakes) and an Analysis of Control Options. Report No. CG-D-11-95, U. S. Coast Guard, Groton CT and U. S. Dept. of Transportation, Washington DC.

Choi, K.-H., W. Kimmerer, G. Smith, G.M. Ruiz, and K. Lion (2006) Post-exchange zooplankton in ballast water of ships entering the San Francisco Estuary. *Journal of Plankton Research* 27: 707-714.

Cohen, A.N. 1998. Ships' Ballast Water and the Introduction of Exotic Organisms into the San Francisco Estuary: Current Status of the Problem and Options for Management. A report for CALFED and the California Urban Water Agencies. San Francisco Estuary Institute, Richmond CA.

Cohen, A.N. and B. Foster. 2000. The regulation of biological pollution: Preventing exotic species invasions from ballast water discharged into California coastal waters. Golden Gate University Law Review 30(4): 787-883.

Connelly, S.J., E.A. Wolyniak, K.L. Dieter, C.E. Williamson, and K.L. Jellison (2007) Impact of zooplankton grazing on the excystation, viability, and infectivity of the protozoan pathogens *Cryptosporidium parvum* and *Giardia lamblia. Applied and Environmental Microbiology* 73: 7277-7282.

Cohen, A.N. (1998) Ships' Ballast Water and the Introduction of Exotic Organisms into the San Francisco Estuary: Current Problem Status and Management Options. Report for California Bay Delta Authority, Sacramento, CA. San Francisco Estuary Institute, Richmond, CA.

CSLC. 2009. 2009 Assessment of the Efficacy, Availability and Environmental Impacts of Ballast Water Treatment Systems for Use in California Waters. California State Lands Commission, Sacramento, CA. 180 pages.

CSLC. 2010. 2010 Assessment of the Efficacy, Availability and Environmental Impacts of Ballast Water Treatment Systems for Use in California Waters. California State Lands Commission, Sacramento, CA. 141 pages.

Cuker, B.E. and L. Hudson Jr. (1992) Type of suspended clay influences zooplankton response to phosphorus loading. *Limnology and Oceanography* 37: 566-576.

Dames and Moore. 1998. Ballast Water Management Technical Memorandum for the Port of Oakland. Job No. 02801-028-086, November 6, 1998. Dames and Moore, San Francisco, CA.

Dames and Moore. 1999. Phase I Final Report Ballast Water Exchange and Treatment. A Report for the California Association of Port Authorities, Pacific Merchant Shipping Association, Steamship Association of Southern California, and Western States Petroleum Association. Dames and Moore, San Francisco, CA.

Darzynkiewicz, Z., X. Li, and J. Gong (1994) Assays of cell viability: Discrimination of cells dying by apoptosis. In: *Methods in Cell Biology,* by Z. Darzynkiewicz, J.P. Robinson, and H.A. Crissman (eds.). Academic Press, New York.

Dobbs, F.C., and A. Rogerson (2005) Ridding ships' ballast water of microorganisms. *Environmental Science and Technology* 39: 259A-264A.

Doblin, M.A. and F.C. Dobbs (2006) Setting a size-exclusion limit to remove toxic dinoflagellate cysts in ships' ballast water. *Marine Pollution Bulletin* 52: 259-263.

Dobroski, N., C. Scianni, D. Gehringer, and M. Falkner (2009) 2009 Assessment of the Efficacy, Availability and Environmental Impacts of Ballast Water Treatment Systems for Use in California Waters. Produced for the California State Legislature. Available at: http://www.slc.ca.gov/spec_pub/mfd/ballast_water/documents/2009cslctechreportfinal.pdf

Drake, J.M., D.M. Lodge and M. Lewis. 2005. Theory and preliminary analysis of species invasions from ballast water: controlling discharge volume and location. *American Midland Naturalist* 154:459-470.

Elliot, J.M. (1971) *Some Methods for the Statistical Analysis of Samples of Benthic Invertebrates.* Scientific Publication No. 25, Freshwater Biological Association, Windermere, UK.

Faruque, S., M.J. Albert, and J.J. Mekalanos (1998) Epidemiology, genetics, and ecology of toxigenic Vibrio cholerae. *Microbiology and Molecular Biology Reviews* 62: 1301-1314.

Fuhrman, J.A. (1999) Marine viruses and their biogeochemical and ecological effects. *Nature* 399: 541-548.

Garvey, M., B. Moriceau, and U. Passow (2007) Applicability of the FDA assay to determine the viability of marine phytoplankton under different environmental conditions. *Marine Ecology Progress Series* 352: 17-26.

Gauthier, D. and D.A. Steel. 1996. A Synopsis of the Situation Regarding the Introduction of Nonindigenous Species by Ship-Transporting Ballast Water in Canada and Selected Countries. Canadian Manuscript Report of Fisheries and Aquatic Sciences No. 2380. Marine Environmental Sciences Division, Department of Fisheries and Oceans, Maurice Lamontagne Institute, Mont-Joli (Quebec), Canada.

Glosten. 2002. Pacific Ballast Water Treatment Pilot Project: Ballast Water Transfer Study: Technical Feasibility with Associated Capital Costs. Prepared for the Port of Seattle, Seattle, WA. File No. 01080. The Glosten Associates, Seattle, WA. 36 pages.

Gollasch, S. (2010) *Global Expert Workshop on Harmonization of Methodologies for Test Facilities of Ballast Water Management Systems*. Workshop Report. World Maritime University, Malmö, Sweden, 39 pp.

Gollash, S. and M.J.W. Veldhuis. 2008. Final report of the shipboard testing of the SEDNA® System, for Type Approval according to Regulation D2 and the relevant IMO Guideline (June-December 2007) Shipboard testing on board OOCL Finland. BSH/M5101, NIOZ, Royal Netherlands Institute for Sea Research, Texel, The Netherlands.

Greenman, D., K. Mullen and S. Parmar. 1997. Ballast Water Treatment Systems: A Feasibility Study. Produced in cooperation with ENS Chris Freise, U.S. Coast Guard Office of Response. Commissioned by the U.S. Coast Guard and Worcester Polytechnic Institute. Submitted to Professor Matthew Ward, Washington, D.C. Project Center, Worcester Polytechnic Institute. 59 pages.

Gregg, M.D. and G.M. Hallegraeff (2007) Efficacy of three commercially available ballast water biocides against vegetative microalgae, dinoflagellate cysts and bacteria. *Harmful Algae* 6: 567-584.

Guy, M.D., J.D. McIver and M.J. Lewis. (1977) The removal of virus by a pilot treatment plant. *Water Research* 11(5): 421-428.

Hallegraeff, G.M. (1998) Transport of toxic dinoflagellates via ship's ballast water: bioeconomic risk assessment and efficacy of possible ballast water management strategies. *Marine Ecology Progress Series* 168: 297-309.

Hallegraeff, G.M. and C.J. Bolch (1992) Transport of dinoflagellate cysts in ship's ballast water: Implications for plankton biogeography and aquaculture. *Journal of Plankton Research* 14: 1067-1084.

Hallegraeff, G.M., J.P. Valentine, J.-A. Marshall, and C.J. Bolch (1997) Temperature tolerances of toxic dinoflagellate cysts: application to the treatment of ships' ballast water. *Aquatic Ecology* 31: 47-52.

Hampel, M., I. Moreno-Garrido, C. Sobrino, H.L.M. Lubia, and J. Blasco (2001) Acute toxicity of LAS homologues in marine microalgae: Esterase activity and inhibition growth as endpoints of toxicity. *Ecotoxicology and Environmental Safety* 48: 287-292.

Hendry, G.A.F., J.D. Houghton, and S.B. Brown (1987) The degradation of chlorophyll - a biological enigma. *New Phytologist* 107: 255-302.

Holm-Hansen, O. (1973) The use of ATP determinations in ecological studies. *Bulletin of the Ecological Research Commission (Stockholm)* 17: 215-222.

Hunt, C.D., D.C. Tanis, T.G. Stevens, R.M. Frederick, and R.A. Everett (2005, August 1) Verifying ballast water treatment performance. *Environmental Science and Technology* 321A-328A.

International Maritime Organization (IMO). 1991. International Guidelines for Preventing the Introduction of Unwanted Aquatic Organisms and Pathogens from Ships' Ballast Water and Sediment Discharges. International Maritime Organization, Marine Environment Protection Committee, Resolution MEPC 50(31), adopted 4 July 1991.

International Maritime Organization (IMO). 1993. Guidelines for Preventing the Introduction of Unwanted Aquatic Organisms and Pathogens from Ships' Ballast Water and Sediment Discharges. International Maritime Organization, Resolution A.774(18), adopted 4 November 1993.

International Maritime Organization (IMO). 1997. Guidelines for the Control and Management of Ships' Ballast Water to Minimize the Transfer of Harmful Aquatic Organisms and Pathogens. International Maritime Organization, 20th Assembly, Resolution A.868(20), adopted 27 November 1997.

International Maritime Organization (IMO). 2003. Harmful Aquatic Organisms in Ballast Water. Comments on Draft Regulation E-2. Concentrations of organisms delivered in ships' ballast water in the absence of any treatment: Establishing a baseline for consideration of treatment efficacy. MEPC 49/2/21, 49th Session/Agena Item 2, Marine Environment Protection Committee, International Maritime Organization, London (May 23, 2003).

International Maritime Organization (IMO). 2004. International Convention for the Control and Management of Ships' Ballast Water and Sediments, 2004. International Maritime Organization, International Conference on Ballast Water Management for Ships.

International Maritime Organization (IMO). 2005a. Guidelines tor Ballast Water Management Equivalent Compliance (G3). International Maritime Organization, Marine Environment Protection Committee, Resolution MEPC 123(53), adopted 22 July 2005.

International Maritime Organization (IMO). 2005b. Guidelines for Ballast Water Management and Development of Ballast Water Management Plans (G4). International Maritime Organization, Marine Environment Protection Committee, Resolution MEPC 127(53), adopted 22 July 2005.

International Maritime Organization (IMO). 2006. Guidelines for Ballast Water Reception Facilities (G5). International Maritime Organization, Marine Environment Protection Committee, Resolution MEPC 153(55), adopted 13 October 2006.

International Maritime Organization (IMO) (2008b) Annex 4 Resolution MEPC.174(58). *Guidelines for Approval of Ballast Water Management Systems (G8)*. Available at: http://www.regulations.gov/search/Regs/home.html#documentDetail?R=09000064807e8904.

International Maritime Organization (IMO) (2008b) Annex 1 Resolution MEPC.169(57). *Procedure for Approval of Ballast Water Management Systems that Make Use of Active Substances (G9)*. Available at: http://www.regulations.gov/search/Regs/home.html#documentDetail?R=09000064807e890e.

International Maritime Organization (IMO) (2009) Harmful Aquatic Organisms in Ballast Water. Type Approval of the Hyde Guardian™ Ballast Water Management System. Submitted by the United Kingdom. International Maritime Organization, Marine Environment Protection Committee, 59th session, Agenda item 2, MEPC 59/INF.20.

Inubushi, K., P.C. Brookes, and D.S. Jenkinson (1989) Adenosine 5'-triphosphate and adenylates energy charge in waterlogged soil. *Soil Biology and Biochemistry* 21: 733-739.

Jeffrey, S.W. and M. Vest (1997) Introduction to marine phytoplankton and their pigment signatures, pp. 37-87. In: *Phytoplankton Pigments in Oceanography*, by S.W. Jeffrey, R.F.C. Mantoura, and S.W. Wright (eds.). The United Nations Educational, Scientific, and Cultural Organization (UNESCO), Paris.

Johnson, W.S. and D.M. Allen (2005) *Zooplankton of the Atlantic and Gulf Coasts – A Guide to Their Identification and Ecology*. John Hopkins University Press, Baltimore, MD.

Kaneshiro, E.S., M.A. Wyder, Y.-P. Wu, and M.T. Cushion (1993) Reliability of calcein acetoxy methyl ester and ethidium homodimer or propidium iodide for viability assessment of microbes. *Journal of Microbiological Methods* 17: 1-16.

Kardinaal, W.E.A., L. Tonk, I. Janse, S. Hol, P. Slot, J. Huisman, and P. Visser (2007) Competition for light between toxic and nontoxic strains of the harmful cyanobacterium Microcystis. *Applied and Environmental Microbiology* 73: 2939-2946.

Karl, D.M. (1980) Cellular nucleotide measurements and applications in microbial ecology. *Microbiological Reviews* 44: 739-796.

Keasey, K. and P. Moon (2000) Sunk cost effects: a test of the importance of context. Economics Letters 66(1): 55-58.

Keller, R.P., J.M. Drake, M.B. Drew and D.M. Lodge. 2010. Linking environmental conditions and ship movements to estimate invasive species transport across the global shipping network. *Diversity and Distributions* DOI: 10.1111/j.1472-4642/2010/00696x

Kieft, T.L. and L.L. Rosaker (1991) Application of respiration and adenylates-based soil microbiological assays to deep subsurface terrestrial sediments. *Soil Biology and Biochemistry* 23: 563-568.

King, D.M. and M.N. Tamburri (2010). Verifying compliance with ballast water discharge regulations. *Ocean Development & International Law* 41:152-165.

Klemm, D.J., G.E. Morrison, T.J. Norberg-King, W.H. Peltier, and M.A. Heber (1994) *Short-Term Methods for Estimating the Chronic Toxicity of Effluents and Receiving Waters to Marine and Estuarine Organisms,* 2nd edition. Report #EPA/600/4-91/003. U.S. EPA, Washington, DC.

Knoechel, R. and J. Kalff (1978) An *in situ* study of the productivity and population dynamics of five freshwater plankton diatom species. *Limnology and Oceanography* 23: 195-218.

Kokinos, J.K., T.I. Eglington, M.A. Goni, J.J. Boon, P.A. Martoglio, and D.M. Anderson (1998) Characterization of a highly resistant biomacromolecular material in the cell wall of a marine dinoflagellate resting cyst. *Organic Geochemistry* 28: 265-288.

Laabir M, Gentien P. (1999) Survival of toxic dinoflagellates after gut passage in the Pacific oyster *Crassostrea gigas* Thunberg. *Journal of Shellfish Research* 18: 217-222.

Laughton R., T. Moran and G. Brown. 1992. A Review and Evaluation of Ballast Water Management and Treatment Options to Reduce the Potential for the Introduction of Non-native Species to the Great Lakes. Pollutech Environmental, Ltd., Sarnia, Ontario, prepared for the Canadian Coast Guard, Ship Safety Branch, Ottawa.

Lebaron, P., P. Catala, and N. Parthuisot (1998) Effectiveness of SYTOX-Green stain for bacterial viability assessment. *Applied and Environmental Microbiology* 64: 2697-2700.

LeChevallier, M.W. and K.K. Au. (2004) *Water Treatment and Pathogen Control; Process Efficiency in Achieving Safe Drinking Water*. World Health Organization, Geneva. IWA Pubishing, London.

Lee II, H., D.A. Reusser, M. Frazier, and G. Ruiz (2010) *Density Matters: Review of Approaches to Setting Organism-Based Ballast Water Discharge Standards*. Report # EPA/600/R-10/031. Office of Research and Development, National Health and Environmental Effects Research Laboratory – Western Ecology Division, U.S. EPA

Lemieux, E.J., S. Robbins, K. Burns, S. Ratcliff, and P. Herring (2008) *Evaluation of Representative Sampling for Rare Populations using Microbeads*. Report No. CG-D-03-09, United States Coast Guard Research and Development Center, Groton, CT.

Lloyd's Register. 2010. Ballast Water Treatment Technology: Current Status. Lloyd's Register, London.

Lund, J.W.G., C. Kipling, and E.D. LeCren (1958) The inverted microscope method for estimating algal numbers and the statistical basis of estimations by counting. *Hydrobiologia* 11: 143-170.

MacIsaac, E.A. and J.G. Stockner (1993) Enumeration of phototrophic picoplankton by autofluores-cence microscopy, pp. 187-198. In: *Handbook of Methods in Aquatic Microbial Ecology*, by P.F. Kemp, B.F. Sherr, E.B. Sherr, and J.J. Cole (eds.). Lewis Publishers, CRC Press, Inc., Boca Raton, FL.

MacIsaac, H.J., T.C. Robbins, and M.A. Lewis (2002) Modeling ships' ballast water as invasion threats to the Great Lakes. *Canadian Journal of Fisheries and Aquatic Sciences* 59: 1245-1256.

Mackey, M.D., D.J. Mackey, H.W. Higgins, and S.W. Wright (1996) CHEMTAX – A program for estimating class abundances from chemical markers: Application to HPLC measurements of phytoplankton. *Marine Ecology Progress Series* 144: 265-283.

Marine Environment Protection Committee (2006, 28 Feb.) 54th Session, Agenda item 2 – *Harmful Aquatic Organisms in Ballast Water* – Report of the first meeting of the GESAMP-BWWG. MEPC 54/2/12, IMO.

Marine Environment Protection Committee of Sweden (2006, 21 April) *Harmful Aquatic Organisms in Ballast Water - Basic Approval of Active Substances Used by PureBallast Management System*. International Maritime Organization (IMO). 55th session, Agenda Item 2, MEPC 55/2/5.

Maritime Environmental Resource Center (MERC) (2009a) *Land-Based Evaluations of the Siemens Water Technologies SiCURE™ Ballast Water Management System*. MERC, Chesapeake Biological Laboratory, University of Maryland Center for Environmental Science, Solomons, MD.

Maritime Environmental Resource Center (MERC) (2009b) *Land-Based Evaluation of the Maritime Solutions, Inc. Ballast Water Treatment System*. MERC, Chesapeake Biological Laboratory, University of Maryland Center for Environmental Science, Solomons, MD.

Maritime Environmental Resource Center (MERC) (2009c) *Test Plan for the Performance Evaluation of the Severn Trent De Nora BalPure™ BP-2000 Ballast Water Management System*. Chesapeake Biological Laboratory, University of Maryland Center for Environmental Science, Solomons, MD.

Maritime Environmental Resource Center (MERC) (2009d) M/V *Cape Washington* Ballast Water Treatment Test Facility Validation. Chesapeake Biological Laboratory, University of Maryland Center for Environmental Science, Solomons, MD.

Marret, F. and K.A.F. Zonneveld (2003) Atlas of modern organic-walled dinoflagellate cyst distribution. *Review of Palaeobotany and Palynology* 125: 1-200.

Matsuoka, K. and Y. Fukuyo (2000) *Technical Guide for Modern Dinoflagellate Cyst Study*. Available at: http://dinos.anesc.u-tokyo.ac.jp/technical_guide/main.pdf.

Miller, A.W., K. Lion, M.S. Minton and G.M. Ruiz. 2007. Status and Trends of Ballast Water Management in the United States. Third Biennial Report of the National Ballast Information Clearinghouse (January 2004 to December 2005). Submitted to the U.S. Coast Guard. National Ballast Information Clearinghouse, Smithsonian Environmental Research Center, Edgewater, MD.

Minton, M.S., Verling, E., Miller, A.W. and Ruiz, G.M. 2005. Reducing propagule supply and coastal invasions via ships: effects of emerging strategies. Frontiers in Ecology and the Environment 3: 304-308.

Montagnes, D.J.S. and D.H. Lynn (1993) A quantitative protargol stain (QPS) for ciliates and other protists, pp. 229-240. In: *Handbook of Methods in Aquatic Microbial Ecology*, by P.F. Kemp, B.F. Sherr, E.B. Sherr, and J.J. Cole (eds.). Lewis Publishers, CRC Press, Inc., Boca Raton, FL.

Montresor, M., L. Nuzzo, and M.G. Mazzocchi (2003) Viability of dinoflagellate cysts after the passage through the copepod gut. *Journal of Experimental Marine Biology and Ecology* 287: 209-221.

Mosher, J.J., B.S. Levison, and C.G. Johnston (2003) A simplified dehydrogenase enzyme assay in contaminated sediment using 2-(p-iodophenyl)-3(p-nitrophenyl)-5-phenyl tetrazolium chloride. *Journal of Microbiological Methods* 53: 411-415.

Murphy, K.R., D. Ritz, and C.L. Hewitt (2002) Heterogeneous zooplankton distribution in a ship's ballast tanks. *Journal of Plankton Research* 24: 729-734.

Myers, Glenford J. (1979) *The Art of Software Testing.* John Wiley & Sons, New York, pp. 12-13,128.

NRC Marine Board. 1996. Stemming the Tide: Controlling Introductions of Nonindigenous Species by Ships' Ballast Water. Committee on Ships' Ballast Operations, Marine Board, Commission on Engineering and Technical Systems, National Research Council. National Academy Press, Washington, D.C.

National Environmental Services Center (NESC) (2000a) *Slow Sand Filtration. Tech Brief: A National Drinking Water Clearinghouse Fact Sheet*. National Environmental Services Center, West Virginia University. Morgantown, WV.

National Environmental Services Center (NESC) (2000b) *Ultraviolet Disinfection. Tech Brief: A National Drinking Water Clearinghouse Fact Sheet*. National Environmental Services Center, West Virginia University. Morgantown, WV.

National Science Foundation (NSF) (2003) *Engineering Controls for Ballast Water Discharge: Developing Research Needs*. Report of a workshop held on April 28-30, Seattle, WA. Bioengineering and Environmental Systems Division of the Engineering Directorate, NSF, Arlington, VA.

NEI. 2007. Application for Type Approval Certification, NEI Treatment Systems' Venturi Oxygen Stripping Ballast Water Management System, under: IMO Guidelines for Approval of Ballast Water Management Systems (G8). Submitted to the Liberian International Ship and Corporate Register by NEI Treatment Systems, LLC, Los Angeles, California.

New Zealand. 1998. Import Health Standard For Ships' Ballast Water From All Countries (Biosecurity Act 1993). New Zealand Ministry of Agriculture and Forestry, Wellington.

New Zealand. 2005. Import Health Standard For Ships' Ballast Water From All Countries. Issued pursuant to Section 22 of the Biosecurity Act 1993. New Zealand Ministry of Agriculture and Forestry, Wellington.

Oemke, D. 1999. The Treatment of Ships' Ballast Water. EcoPorts Monograph Series No. 18, Ports Corporation of Queensland, Brisbane, Australia. 102 pages.

Oliver, J.D. (1993) Formation of viable but nonculturable cells, pp. 239-272. In: *Starvation in Bacteria*, by S. Kjelleberg (ed.). Plenum Press, New York.

Parsons, M.G. (1998) Flow-through ballast water exchange. *Society of Naval Architects and Marine Engineers (NAME) Transactions* 106: 485-493.

Parsons, M.G. and M. Kotinis. 2008. Further Development and Optimization of the Ballast-Free Ship Design Concept. Final Report. Great Lakes Maritime Research Institute, University of Wisconsin-Superior and University of Minnesota-Duluth.

Petterson, S.R., R.S. Signor, and N.J. Ashbolt (2007) Incorporating method recovery uncertainties in stochastic estimates of raw water protozoan concentrations for QMRA [quantitative microbial risk assessment]. *Journal of Water and Health* 05. Suppl. 1: 51-65.

Phillips, S. (2006) *Ballast Water Issue Paper*. Report for the Pacific States Marine Fisheries Commission. Portland, OR. 34 pp. (http://www.aquaticnuisance.org/wordpress/wp-content/uploads/2009/01/ballast_water_issue_paper.pdf).

Pollutech. 1992. A Review and Evaluation of Ballast Water Management and Treatment Options to Reduce the Potential for the Introduction of Non-native Species to the Great Lakes. Pollutech Environmental, Ltd., Sarnia, Ontario, prepared for the Canadian Coast Guard, Ship Safety Branch, Ottawa.

Porra, R.J. (1991) Recent advances and re-assessments in chlorophyll extraction and assay procedures for terrestrial, aquatic, and marine organisms, including recalcitrant algae, pp. 31-57. In: *Chlorophylls*, by H. Scheer (ed.). CRC Press, Boca Raton, FL.

Porter, J., J. Diaper, C. Edwards, and R. Pickup (1995) Direct measurements of natural planktonic bacterial community viability by flow cytometry. *Applied and Environmental Microbiology* 61: 2783-2786.

Posch, T., J. Pernthaler, A. Alfreider, and R. Psenner (1997) Cell-specific respiratory activity of aquatic bacteria studied with the tetrazolium reduction method, cyto-clear slides, and image analysis. *Applied and Environmental Microbiology* 63: 867-873.

Reavie, E.D., A.A. Cangelosi, and L.E. Allinger (2010) Assessing ballast water treatments: Evaluation of viability methods for ambient freshwater microplankton assemblages. *Journal of Great Lakes Research* 36: 540-547.

Reeves, E. 1998. Protection of the Great Lakes from Infection by Exotic Organisms in Ballast Water. Report for Ninth US Coast Guard District, Cleveland OH.

Reeves, E. 1999. Exotic Policy: An IJC White Paper On Policies for the Prevention of the Invasion of the Great Lakes by Exotic Organisms. Documents on Water Law, College of Law, University of Nebraska - Lincoln. 132 pages.

Rigby, G. and A.H. Taylor. 2001a. Ballast Water Treatment to Minimize the Risks of Introducing Nonindigenous Marine Organisms into Australian Ports. Ballast Water Research Series Report No. 13, Australian Government Department of Agriculture, Fisheries, and Forestry, Canberra. 93 pages.

Rigby, G. and A. Taylor. 2001b. Ballast water management and treatment options. Transactions of the Institute of Marine Engineers 113(3): 79-99.

Romano, G., A. Ianora, L. Santella, and A. Miralto (1996) Respiratory metabolism during embryonic subitaneous and diapause development in *Pontella mediterranea* (Crustacea, Copepoda). *Journal of Comparative Physiology* 166: 157-163.

Rosacker, L.L. and T. L. Kieft (1990) Biomass and adenylate energy charge of a grassland soil during drying. *Soil Biology and Biochemistry* 22: 1121-1127.

Roth, B.L., M. Poot, S.T. Yue, and P.J. Millard (1997) Bacterial viability and antibiotic susceptibility testing with SYTOX-Green nucleic acid stain. *Applied and Environmental Microbiology* 63: 2421-2431.

Ruiz, G.M. and D.F. Reid (2007) Current State of Understanding About the Effectiveness of Ballast Water Exchange (BWE) in Reducing Aquatic Nonindigenous Species (ANS) Introductions to the Great Lakes Basin and Chesapeake Bay, USA. Synthesis and Analysis of Existing Information, NOAA Technical Memorandum GLERL-142.

Ruiz, G.M., G.E. Smith, and M. Sytsma (2006) *Workshop Report on Testing of Ballast Water Treatment Systems: General Guidelines and Step-wise Strategy Toward Shipboard Testing*. Aquatic Bioinvasion Research and Policy Institute, a joint program of the Smithsonian Environmental Research Center (SERC) and Portland State University (PSU). Submitted to the Pacific States Marine Fisheries Commission, Alaska Department of Fish and Game, and Prince William Sound Regional Citizens Advisory Council.

Sandrin, T.R., D.C. Herman, and R.M. Maier (2009) Physiological methods, pp. 191-223. In: *Environmental Microbiology*, by R.M. Maier, I.L. Pepper, and C.P. Gerba (eds.). Elsevier, New York, NY.

Sarmento, H. and J.-P. Descy (2008) Use of marker pigments and functional groups for assessing the status of phytoplankton assemblages in lakes. Journal of Applied Phycology 20: 1001-1011.

Schlüter, L., T.L. Lauridsen, G. Krogh, and T. Jørgense (2006) Identification and quantification of phytoplankton groups in lakes using new pigment ratios - a comparison between pigment analysis by HPLC and microscopy. *Freshwater Biology* 51: 1474-1485.

Schmid, H., F. Bauer, and H.B. Stich (1998) Determination of algal biomass with HPLC pigment analysis from lakes of different trophic state in comparison to microscopically measured biomass. *Journal of Plankton Research* 20: 1651-1661.

Selvin, R., B. Reguera, I. Bravo, and C.M. Yentsch (1988) Use of fluorescein diacetate (FDA) as a single-cell probe of metabolic activity in dinoflagellates cultures. *Biological Oceanography* 6: 505-511.

Sherr, E.B., D.A. Caron, and B.F. Sherr (1993) Staining of heterotrophic protists for visualization via epifluorescence microscopy, pp. 213-228. In: *Handbook of Methods in Aquatic Microbial Ecology*, by P.F. Kemp, B.F. Sherr, E.B. Sherr, and J.J. Cole (eds.). Lewis Publishers, CRC Press, Inc., Boca Raton, FL.

Sherr, E.B. and B.F. Sherr (1993) Preservation and storage of samples for enumeration of heterotrophic protists, pp. 207-212. In: *Handbook of Methods in Aquatic Microbial Ecology*, by

P.F. Kemp, B.F. Sherr, E.B. Sherr, and J.J. Cole (eds.). Lewis Publishers, CRC Press, Inc., Boca Raton, FL.

Songster-Alpin, M.S. and R.L. Klotz (1995) A comparison of electron transport system activity in stream and beaver pond sediments. *Canadian Journal of Fisheries and Aquatic Sciences* 52: 1318-1326.

Steinberg, M.K., S.C. Riley, S.H. Robbins, B.N. Nelson, E.J. Lemieux, and L.A. Drake (2010) Geovalidation of a method to determine the viability of organisms ≥ 10 μm and < 50 μm (nominally protists) in ships' ballast water using two vital, fluorescent stains. *NRL Letter Report* 6130/xxxx, Washington, DC (in press).

Stevens, T.G., R.M. Frederick, R.A. Everett, J.T. Hurley, C.D. Hunt, and D.C. Tanis (2004) Performance verification of ballast water treatment technologies by USEPA/NSF Environmental Technology Verification Program. In: *Proceedings of the 2nd International Ballast Water Treatment R&D Symposium*, by J.T. Matheickal and S. Raaymakers (eds.). IMO, London, UK.

Sugita, H., T. Mitsaya, K. Amanuma, K. Hayashi, T. Asai, C. Maruyama and Y. Degechi. (1992) Ultraviolet susceptibility of three marine fish pathogens. *Bulletin of the College of Agriculture and Veterinary Medicine* 49: 117-121.

Suttle, C. (2005) Viruses in the sea. *Nature* 437: 356-361.

Tagg, R. 1999. Ballast Water Management for Containerships: Implications for the Port of Oakland. Report for the Port of Oakland. Herbert Engineering Corp., San Francisco, CA.

Takano, C.T., C.E. Folsome, and D.M. Karl (1983) ATP as a biomass indicator for closed ecosystems. *BioSystems* 44: 739-796.

Tamburri, M. 2009. Land-Based Evaluations of the Maritime Solutions, Inc. Ballast Water Treatment System. UMCES Technical Report Series: Ref. No. [UMCES]CBL 09-138, Chesapeake Biological Laboratory, Solomons, MD.

Turner, R. E. (1978) Variability of the reverse-flow concentration technique of measuring plankton respiration. *Estuaries* 1: 65-68.

United Nations Environmental Programme (UNEP) (2000) International Source Book on Environmentally Sound Technologies for Wastewater and Stormwater Management. United Nations Environment Programme, Division of Technology, Industry and Economics. Accessed at http://www.unep.or.jp/ietc/publications/techpublications/techpub-15/3-4AmericaNorth/4-1_1.asp on Dec. 5, 2010.

United States Census Bureau (2010) The 2010 Statistical Abstract. The National Data Book. Table 27. Incorporated Places With 100,000 or More Inhabitants in 2008—Population. Downloaded at http://www.census.gov/compendia/statab/cats/population.html on Dec. 5, 2010.

US Coast Guard. 1999. Implementation of the National Invasive Species Act of 1996 (NISA). Interim rule. U.S. Federal Register 64(94): 26672-26690 (May 17, 1999).

US Coast Guard. 2001. Implementation of the National Invasive Species Act of 1996 (NISA). Final rule. U.S. Federal Register 66(225): 58381-58393 (November 21, 2001).

US Coast Guard. 2004. Mandatory Ballast Water Management Program for U.S. Waters. U.S. Federal Register 69(144): 44952-44961 (July 28, 2004).

United States Coast Guard (USCG) (2001) Report to Congress on the Voluntary National Guidelines for Ballast Water Management. Washington D.C.

US Coast Guard. 2008. Ballast Water Discharge Standard - Draft Programmatic Environmental Impact Statement. U. S. Coast Guard, Washington, D.C. 218 pages.

US Congress. 1990. Nonindigenous Aquatic Nuisance Prevention and Control Act of 1990. U.S. Congress, Public Law 101-6461, enacted on November 29, 1990.

US Congress. 1996. National Invasive Species Act of 1996. U.S. Congress, Public Law 104-332, enacted on October 26, 1996.

United States Environmental Protection Agency (U.S. EPA) (1991) *Guidance Manual for Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources*. Science and Technology Branch, Criteria and Standards Division, Office of Drinking Water, U.S. Environmental Protection Agency, Washington, DC.

United States Environmental Protection Agency (U.S. EPA) (1993) *Methods for the Determination of Inorganic Substances in Environmental Samples*. Report 600/R-93-100. Office of Research and Development, U.S. EPA, Washington, DC.

United States Environmental Protection Agency (U.S. EPA) (1997) *Method 445.0: In vitro Determination of Chlorophyll* a *and Pheophytin* a *in Marine and Freshwater Algae by Fluorescence*. U.S. EPA, Cincinnati, OH.

United States Environmental Protection Agency (U.S. EPA) (1997b) *Small System Compliance Technology List for the Surface Water Treatment Rule*. EPA 815-R-97-002, Office of Water, U.S. Environmental Protection Agency, Washington, DC.

United States Environmental Protection Agency (1999) *Criteria for Evaluation of Proposed Protozoan Detection Methods*. Report #EPA 815-K-99-02. Office of Research and Development, U.S. EPA, Cincinnati, OH. Available at: http://www.epa.gov/microbes/critprot.pdf.

US EPA. 2001. Aquatic Nuisance Species In Ballast Water Discharges: Issues and Options. Draft Report for Public Comment – September 10, 2001. U.S. Environmental Protection Agency Office of Water, Office of Wetlands, Oceans and Watersheds, Office of Wastewater Management, Washington, D.C.

United States Environmental Protection Agency (U.S. EPA) (2002a) *Methods for Measuring the Acute Toxicity of Effluents to Freshwater and Marine Organisms*, 5th Edition. Report # EPA 821-R-02-012. Office of Water, U.S. EPA, Washington, DC.

United States Environmental Protection Agency (U.S. EPA) (2002b) *Short-Term Methods for Estimating the Chronic Toxicity of Effluents and Receiving Waters to Freshwater Organisms*, 4th Edition. Report # EPA 821-R-02-013. Office of Water, U.S. EPA, Washington, DC.

United States Environmental Protection Agency (U.S. EPA) (2002c) *Short-Term Methods for Estimating the Chronic Toxicity of Effluents and Receiving Waters to Marine and Estuarine Organisms*, 3rd edition. Report # EPA 821-R-02-014. Office of Water, U.S. EPA, Washington, DC.

United States Environmental Protection Agency (U.S. EPA) (2003) *Ambient Water Quality Criteria for Dissolved Oxygen, Water Clarity and Chlorophyll a for the Chesapeake Bay and Its Tidal Tributaries*. Report EPA 903-R-03-002. Office of Water, U.S. EPA, Washington, DC.

United States Environmental Protection Agency (U.S. EPA) (2004) *Toolkit for Assessing Potential Allegations of Environmental Justice*. EPA 300-R-04-002, Office of Environmental Justice, U.S. Environmental Protection Agency, Washington.

United States Environmental Protection Agency (U.S. EPA) (2010, July) *Environmental Technology Verification Program (ETV) Draft Generic Protocol for the Verification of Ballast Water Treatment Technologies*, Version 5.0. U.S. EPA ETV in cooperation with the U.S. Coast Guard Environmental Standards Division (CG-5224) and the U.S. Naval Research Laboratory. National Sanitation Foundation International (NSF), Ann Arbor, MI, 62 pp. + appendices.

United States Environmental Protection Agency (U.S. EPA) (2010b) *Interim Guidance on Considering Environmental Justice During the Development of an Action*. OPEI Regulatory Development Series, U.S. Environmental Protection Agency, Washington.

Veldhuis, M.J.W. 2009. Final report of the land-based testing of the Hyde-Guardian™-System, for Type Approval according to the Regulation D-2 and the relevant IMO Guideline (April-July 2008). NIOZ, Royal Netherlands Institute for Sea Research, Texel, The Netherlands.

Veldhuis, M.J.W., T.L. Cucci, and M.E. Sieracki (1997) Cellular DNA content of marine phytoplankton using two new fluorochromes: taxonomic and ecological implications. *Journal of Phycology* 33: 527-541.

Veldhuis, M.J.W. and F. Fuhr. 2008. Final report of the landbased testing of the SEDNA® System, for Type Approval according to Regulation D2 and the relevant IMO Guideline (April-July 2007). BSH/M5101, NIOZ, Royal Netherlands Institute for Sea Research, Texel, The Netherlands.

Veldhuis, M.J.W., G.W. Kraaij, and K.R. Timmermans (2001) Cell death in phytoplankton: correlation between changes in membrane permeability, photosynthetic activity, pigmentation and growth. *European Journal of Phycology* 36:1-13.

Vézie, C., J. Rapala, J. Vaitomaa, J. Seitsonen, and K. Sivonen (2007) Effect of nitrogen and phosphorus on growth of toxic and nontoxic *Microcystis* strains and on intracellular microcystin concentrations. *Microbial Ecology* 43: 443-454.

Victoria ENRC. 1997. Report on Ballast Water and Hull Fouling in Victoria. Parliament of Victoria, Environmental and Natural Resources Committee. Victorian Government Printer, Melbourne, Australia.

Vollenweider, R.A. (ed.) (1974) *A Manual on Methods for Measuring Primary Production in Aquatic Environments*, 2nd edition. International Biological Program Handbook No. 12, Blackwell Scientific, Oxford, U.K.

Wang, X.C., F.G. Qiu and P.K. Jin. 2006. Safety of treated water for re-use purposes—comparison of filtration and disinfection processes. *Water Science & Technology* 53(9): 213-220.

Welschmeyer, N. 2005. Presentation on Shipboard Trials of the Optimar Ballast Water Treatment System. California Ballast Water Performance Standards Technical Advisory Panel Meeting (April 27, 2005), California State Lands Commission, Sacramento.

Wetzel, R.G. (2001) *Limnology*, 3rd edition. Academic Press, New York, NY.

Wetzel, R.G. and G.E. Likens (2000) *Limnological Analyses*, 3rd edition. Springer-Verlag, New York.

Williams, S.C., Y. Hong, D.C.A. Danavall, M.H. Howard-Jones, D. Gibson, M.E. Frischer, and P.G. Verity (1998) Distinguishing between living and nonliving bacteria: Evaluation of the vital stain propidium iodide and its combined use with molecular probes in aquatic samples. *Journal of Microbiological Methods* 32: 225-236.

Wonham, M.J., W.C. Walton, G.M. Ruiz, A.M. Frese, and B.S. Galil (2001) Going to the source: role of the invasion pathway in determining potential invaders. *Marine Ecology Progress Series* 215: 1-12.

World Health Organization (WHO) (2008) *Guidelines for Drinking-water Quality. Third Edition. Incorporating the First and Second Addenda. Volume 1: Recommendations*. World Health Organization, Geneva.

Zhang, F. and M. Dickman (1999) Mid-ocean exchange of container vessel ballast water. 1. Seasonal factors affecting the transport of harmful diatoms and dinoflagellates. *Marine Ecology Progress Series* 176: 243-251.

Zurawell, R.W., H. Chen, J.M. Burke, and E.E. Prepas (2005) Hepatotoxic cyanobacteria: A review of the biological importance of microcystins in freshwater environments. *Journal of Toxicology and Environmental Health, Part B*, 8: 1-37.