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The significance of dilution in evaluating possible impacts of wastewater discharges from large cruise ships

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Abstract

In response to public concerns about discharges from large cruise ships, Alaska's Department of Environmental Conservation (ADEC) sampled numerous effluents in the summer of 2000. The data showed that basic marine sanitation device (MSD) technology for black water (sewage) was not performing as expected. Untreated gray water had high levels of conventional pollutants and surprisingly high levels of bacteria. Both black water and gray water discharges sometimes exceeded state water quality standards for toxicants. The state convened a Science Advisory Panel (the Panel) to evaluate impacts associated with cruise ship wastewater discharges. The effluent data received wide media coverage and increased public concerns. Consequently, legislative decisions were made at the State and Federal level, and regulations were imposed before the Panel completed its evaluation. The Panel demonstrated that following the rapid dilution from moving cruise ships, the effluent data from the Summer of 2000 would not have exceeded water quality standards, and environmental effects were not expected.

Keywords: Cruise ships; Wastewater; Dilution; Sewage; Black water; Gray water; Pollution

1. Introduction

The study of effluent characteristics, by itself, is not sufficient to evaluate exposure and ecological/health risks associated with any wastewater discharge and especially a discharge from a large, moving ship. An understanding of dilution in the context of a vessel moving and generating a propeller mixed wake during discharge is essential. The Science Advisory Panel (the Panel), convened by the State of Alaska, undertook a number of efforts with the goal of developing a simple method of estimating wastewater dilution in the wake of a moving large cruise ship.[2] Starting in February 2001 and continuing through September 2002 the Panel

- reviewed several published wake-mixing studies (Colonell et al., 2000; Katz et al., 2003; Csanady, 1980; Kim, 2000; ESL, 2000) and

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[1] Although released by NOAA, the information in this paper does not reflect, represent, or form any part of the support of the policies of NOAA or the Department of Commerce. Further, release by NOAA does not imply that NOAA or the Department of Commerce agree with the information contained herein.

[2] A large cruise ship is defined in Alaska Statute 46.03.490 as a commercial passenger vessel that provides overnight accommodation for 250 or more passengers for hire, determined with reference to the number of lower berths. Federal regulations written specifically for cruise ships operating in Alaska waters (33 CFR159, Subpart E) apply to vessels with accommodations for 500 or more passengers. In this document, we are using the State definition of large cruise ship.

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- developed a preliminary conservative mixing equation to describe wastewater dispersion behind large moving cruise ships (Science Advisory Panel 2001). The preliminary mixing equation assumed that complete mixing of a discharge occurred in a volume of water described by the width and depth of the vessel, the distance traveled by the vessel, and the rate of discharge to the volume of the receiving water. Because the preliminary equation was thought to be overly conservative, dye dispersion studies were needed to refine the equation.
- The preliminary mixing calculations were used to evaluate an extensive data set from 21 cruise ships obtained by Alaska's Department of Environmental Conservation (ADEC) in the summer of 2000 (Science Advisory Panel 2001).
- Five large cruise ships were visited in order to review how they managed their various waste streams.
- Direct observations of the depth and width of turbulence behind several moving cruise ships were made (Loehr et al., 2001).
- One member observed dye dispersion studies conducted by US EPA's Office of Water for four cruise ships off Miami, Florida.
- Studies conducted by the US Navy behind a frigate that measured and modeled dilution of a pulped waste paper discharge (Katz et al., 2003) were reviewed.
- A draft copy of US EPA's final report on the Miami cruise ship dye studies (US EPA, 2002) was reviewed.

2. Dilution following discharges from large cruise ships

The initial dilution following the discharge of wastewater from a moving large cruise ship is a function of the beam (width), the draft (depth), the speed of the vessel and the rate of effluent discharge. A moving ship displaces a volume of water that is refilled immediately as the ship passes, creating mixing astern of the ship. The ship represents a moving cross-sectional area, the larger it is and the faster it moves, the higher the dilution.

The dye studies conducted by US EPA (2002) were compared to the preliminary mixing equation that the Panel had developed in 2001. The results of the dye studies, and the direct observation of wake turbulence in the water column behind several moving cruise ships demonstrated that the preliminary mixing from the Panel's equation could be increased, resulting in the following equation which calculates the dilution factor for a discharge from a large cruise ship.

2.1. Large cruise ship

$$\begin{aligned}\text{Dilution factor} &= 4 \times (\text{ship width} \times \text{ship draft} \times \text{ship speed})\\ &\quad /(\text{volume discharge rate})\\ &= 4 \times (\_\_\text{m} \times \_\_\text{m} \times \_\_\text{m s}^{-1})/(\_\_\text{m}^3\,\text{s}^{-1})\end{aligned}$$

The mixing equation is quite straightforward. A ship with a large cross-sectional area (draft and width) will create more mixing than a smaller ship. A ship moving faster will discharge less effluent per meter traveled than a ship moving at a lesser rate. A ship discharging at a slower rate will also discharge less effluent per meter traveled. Decreased effluent discharged per meter traveled leads to greater dilution.

Vigorous mixing occurs in the turbulent wake and extends horizontally beyond the beam (or width) and vertically below the draft (or depth) of the vessel. As time passes behind the vessel, the bubbles mixed into the water rise and spread horizontally, adding to the effective mixing. For a large cruise ship discharging at a high rate of 200 cubic meters per hour and traveling at 6 knots, the dilution factor will be greater than 50,000. (Note that industrial and municipal continuous point source discharges in the United States typically have much lower dilution factors, generally in the range of less than 10 and up to 500.) Because large cruise ships often discharge at higher speeds, and at lesser discharge rates, the initial dilution factor of 50,000 is a reasonable worst case (i.e. least dilution). Both the passage of the hull through the water and the agitation caused by the propellers assure that the mixing occurs very rapidly.

The strength of the mixing equation is best illustrated by comparing its calculations with the dilutions determined by US EPA's dye dispersion studies in the wakes of four large cruise ships. A draft report of US EPA's studies was released to the Panel in July 2002 (US EPA, 2002). Because US EPA's observations were of actual cruise ship wastewater discharges, the dye studies provided the best reference for establishing the factor in the Panel's recommended mixing equation.

Three of the large cruise ships used in the dye studies (*M/V Majesty*, *M/V Paradise and M/V Fascination*) had conventional twin propeller arrangements while one (*M/V Explorer*) had a dual azipod propulsion system (external electric motors and propellers with a shroud around them). All four vessels discharged laterally through the side of the hull (rather than downward through the bottom of the hull). The point of discharge was typically around 6 meters below the surface.

The US EPA reported measured and calculated dilution factors. The *M/V Explorer's* measured dilution factor was substantially less than the other vessels. However, the calculated dilution factors for all the vessels were similar. For both the measured and calculated dilution factors, the *M/V Paradise* had the highest dilution factors.

The Panel initially thought that the azipod propulsion may have explained the lower measured dilution factor for the *M/V Explorer*. Closer examination of the draft US EPA report lead the Panel to conclude that the dye in the wastewater tank on the *M/V Explorer* could not have been completely mixed and must have initially discharged at a much higher concentration than was intended. The Panel's analysis was based on a mass-balance calculation comparing the amount of dye discharged per meter traveled (based on the wastewater discharge rate and assuming the dye in

Table 1
Dilution comparisons for four large cruise ships

		Majesty	Explorer	Paradise	Fascination
Width	m	32.6	38.6	31.4	31.4
Depth	m	7.7	8.8	7.75	7.75
Speed	m/sec	8.96	9.78	7.72	4.68
Discharge rate	m^3/h	112	56	68	72
Discharge rate	m^3/s	0.031	0.016	0.019	0.020
US EPA "measured" dilution[a]	Factor	386,057	195,322	643,810	288,412
US EPA "calculated" dilution[a]	Factor	342,123	907,547	666,667	255,449
Panel's "equation" dilution[b]	Factor	289,031	854,309	397,918	227,992
US EPA "measured" dilution divided by US EPA's "calculated" dilution	Ratio	1.12	0.21	0.96	1.13
US EPA "measured" dilution divided by the Panel's "equation" dilution	Ratio	1.3	0.2	1.6	1.3
US EPA "calculated" dilution divided by the Panel's "equation" dilution	Ratio	1.2	1.1	1.7	1.1

[a] From US EPA (2002).
[b] Dilution factor = 4 × (ship width × ship draft × ship speed)/(volume discharge rate).

the tank was completely mixed) to the amount of dye in the water after the ship passed. At the rate of discharge of the effluent, such high dye concentrations as observed would not have been possible had the dye been fully mixed within the tank. When the area in which dye was detected was considered in the later transects behind the ships, bearing in mind that there is quite a variation for each cruise ship, the dilution achieved behind the *M/V Explorer* was reasonably close to that observed for two of the other ships. The measured dilutions assumed a uniform dye concentration in the discharge, and for the *M/V Explorer*, that clearly was not the case. Therefore, for the *M/V Explorer*, only the calculated dilution and not the measured dilution was considered in the Panel's final analysis. Erik Heinen of the US EPA presented the results of US EPA's dye studies at the Oceans 2003 conference in San Diego, California in September, 2003 and agreed that the measured dilution for the *M/V Explorer* should not be used.

Table 1 provides the width, depth, speed and discharge rate of the four cruise ships, followed by the dilution factors determined three different ways. The first two are from US EPA's dye studies (US EPA, 2002) and were reported as measured dilutions and calculated dilutions. The third set of dilution factors were determined from the Panel's mixing equation (Science Advisory Panel 2001), using the actual width, depth, speed and discharge rates. The table then presents three different comparisons of the methods. The first comparison divides the US EPA measured dilutions by the US EPA calculated dilutions. The ratios for three of the ships were 1.12, 0.96 and 1.13 showing fairly good agreement between the two US EPA methods. The ratio for the fourth vessel, the M/V Explorer was 0.21, indicating a significant difference. The second comparison presented in the table is between the US EPA measured dilutions and the dilutions from the Panel's mixing equation. The ratios for three ships were greater than 1 (1.3, 1.6, and 1.3) while the ratio for one ship, the *M/V Explorer*, was only 0.2 (see above). The final comparison in the table is the US EPA's calculated dilution factors divided by the dilutions from the Panel's mixing equation. These ratios are all greater than 1 (1.2, 1.1, 1.7, and 1.1). The table illustrates how the Panel's formula for calculating dilution is conservative when compared to the actual observations by US EPA.

In a short study of opportunity of three cruise ships near Juneau, Alaska (Loehr et al., 2001), the Panel used a fathometer to make simple but detailed observations of the depth and width of turbulent water in the wakes of three cruise ships. The cross-sectional area of turbulence was more than four times the cross-sectional area defined by the draft and beam of the vessels at the water line, providing additional physical evidence supporting the Panel's dilution equation for large cruise ships.

As is evident from the US EPA dye studies, the Panel's recommended dilution equation provides a good agreement with observations in which both the speed (4.7–9.8 m/s or 9–18.8 knots), and the discharge rates (56–112 m^3/h) of the vessels varied by a factor of 2.

3. Alaska's discharge standards for large cruise ships

Under Alaska cruise ship discharge regulations, fecal coliform densities in gray water and black water discharges from large ships may not exceed 200 per 100 mL and total suspended solids may not exceed 150 mg/L. Discharge is only allowed while the vessel is traveling at a minimum speed of 6 knots and is at least 1 nautical mile from shore (Alaska Statute 46.03.463(b) and (c)). A large cruise ship may discharge at any speed and location if they meet much more stringent federal effluent standards.[3] A large cruise ship, not able to meet the above standards, may elect to

[3] The standards established by US Title XIV—Certain Alaska Cruise Ship Operations 1404(c) require that ships must meet the following effluent discharge standards in order to discharge continuously: (1) the discharge satisfies the minimum level of effluent quality specified in 40 CFR 133.102; (2) the geometric mean of the samples from the discharge during any 30-day period does not exceed 20 fecal coliform/100 mL and not more than 10% of the samples exceed 40 fecal coliform/100 mL; (3) concentrations of total residual chlorine may not exceed 10 mg/L. The Act establishing the federal law actually states that chlorine residual cannot exceed 10 μg/L not mg/L. There apparently was a transcription error from the Act to the law that carried forward to the regulations. US EPA and the Coast Guard are in the process of reversing the typo.

hold its wastewaters and discharge them when more than 3 nautical miles from land. Since 2003, more than half of large cruise ships have installed new wastewater treatment technologies that allow them to discharge wastewater continuously in Alaska while the rest have elected to discharge outside of both State (3 miles offshore) and Federal waters (12 miles offshore).

4. Far field dispersion

Depending on the level of treatment, large cruise ships in Alaska may be discharging continuously, or at least one nautical mile from shore, or at least three nautical miles from shore. For those discharging offshore, additional mixing and dispersion following the initial dilution occurs before any effluent reaches the shore. Generally, currents flow parallel to the shoreline and onshore winds are necessary to produce onshore movement of surface waters. The shoreline is the area of most concern for bacterial contamination of shellfish. Under the least favorable conditions, the Panel estimated an additional dilution factor of 100 by the time any of the mixed water might reach the shore (Science Advisory Panel 2001), thus diluting the effluent of a vessel discharging at 200 m^3/h and traveling at 6 knots by a dilution factor of $50{,}000 \times 100$ or 5,000,000.

5. Small passenger vessel[4] dilution

The Panel reviewed two studies of smaller ships (Csanady, 1980 and Katz et al., 2003). The Csanady 1980 study was of discharges from towed barges, and the Katz et al., 2003 study was of a Navy frigate with a single propeller. Based on those studies the Panel adjusted the large ship formula by reducing the factor to 3 to create a small ship formula. The following is recommended for calculating dilution for discharges from small commercial passenger vessels:

5.1. Small cruise ship

$$\begin{aligned}\text{Dilution factor} &= 3 \times (\text{ship width} \times \text{ship draft} \times \text{ship speed})\\ &\quad /(\text{volume discharge rate})\\ &= 3 \times (\_\_\_\text{m} \times \_\_\_\text{m} \times \_\_\_\text{m s}^{-1})/(\_\_\_\text{m}^3\,\text{s}^{-1})\end{aligned}$$

Most of the smaller cruise ships do not have holding tanks, so they are essentially continuous dischargers. Mixing when discharging at anchor or a pier would be considerably reduced and such discharges could be a concern in some areas. Ship discharges differ from land-based point source discharges in that they are mobile, so releases to any particular area are brief, rather than continuous. Because small cruise ships have smaller releases, when their MSD is functioning properly, fecal coliform bacteria or pathogens are unlikely to be a problem, but the Panel recommended they not anchor near any shellfish harvest areas. ADEC has determined that most small ships' MSDs do not function properly on a consistent basis (see Table 14 in ADEC, 2004).

6. Dilution and toxicant data

Priority pollutant data were collected in the summer of 2000 from 21 cruise ships. Samples were from black water, gray water and combined discharges. Gray water discharges included many different specific types of wastes such as galley wastes, butcher shop wastes, laundry wastes, showers and sinks. The data set was from before Alaska and Federal legislation imposed additional treatment requirements on the industry and a time period before many of the cruise ships had installed advanced wastewater treatment systems. This data set is therefore appropriate for evaluating the possible impacts associated with discharges of the time, and also for evaluating the benefit of the requirements imposed by the State and Federal governments. The data set for the summer of 2000 and for samples collected in 2001 is presented in Appendix 6 of the Panel's *The Impact of Cruise Ship Wastewater Discharge on Alaska Waters* report (Science Advisory Panel and ADEC 2002). The 2000 data set clearly showed that a number of toxicants in the wastewater discharges exceeded Alaska's water quality standards. Effluent bacteria data from the same time period were also shown to greatly exceed Alaska's water quality standards (Discussed Further in Section 8). Taken together, the bacteria and toxicant data stirred public outrage, media coverage and governmental responses.

The Panel examined how the initial rapid dilution changes the evaluation of the toxicant data compared to directly comparing the effluent concentrations to the water quality criteria. Rapid dilution is relevant to considering actual potential exposures for aquatic life. Both US EPA and all 50 States typically allow the use of mixing zones in the evaluation and permitting of point source discharges. Alaska's water quality standards are based on US EPA's recommended water quality criteria. The water quality criteria include a duration component. Acute criteria generally are based on organisms not receiving more than a one-hour exposure to levels above the criteria more than once every three years. Chronic criteria are generally based on organisms not receiving more than a four-day exposure to levels above the criteria more than once every three years. Both US EPA and Alaska specifically acknowledge a way to consider duration of exposure for acute mixing zones.

US EPA (1991) describes how an acute mixing zone should be established to prevent lethality to passing organisms. The guidance recognizes that the water quality criteria include duration of exposure considerations. Specifically, US EPA allows that a drifting organism

[4] AS 46.03.490 defines a small commercial passenger vessel as one that carries between 50 and 249 passengers for hire with reference to the number of lower berths. This category captures both small cruise ships and some ferries.

should not be exposed to 1-h average concentrations exceeding the acute criteria, and that if travel time for a drifting organism through the acute mixing zone is less than 15 min, then a 1-h average exposure would not be expected to exceed the acute criterion. The same demonstration is allowed for in Alaska's Water Quality Standards at 18 AAC 70.255(d). The Panel views the rapid initial dilution calculated from the recommended mixing equation as occurring within 15 min following the discharge.

Appendix 2 in the Panel's report (Science Advisory Panel and ADEC 2002) presented a table that showed for each priority pollutant from the Summer 2000 data set the number of samples analyzed; the number of samples with detections; the detection limits; the maximum concentrations detected in gray water, black water and/or combined discharges; the average concentrations in the data set; the waste concentrations after an initial dilution factor of 50,000; and the applicable State criteria for marine waters. A condensed version, showing only the maximum concentrations detected, for those priority pollutants where there were detections, and where there was a state water quality standard for comparison is presented in Table 2. The table shows the pollutant, the state water quality standard, the maximum concentration detected, and the concentration after a minimum dilution factor of 50,000.

The Summer 2000 data set represented discharges before Alaska and the Federal Government imposed new treatment requirements or discharge restrictions. After consideration of the initial rapid dilution, no large cruise ship discharge from the Summer 2000 data set resulted in an exceedance of any of the State toxicant water quality standards during underway discharge. However, many of the same discharges would have presented water quality problems if they occurred while the vessel was stationary, because the dilution benefit would be greatly reduced.

The list of priority pollutants is an old list and there are new chemicals used throughout the world that may be more important even though there are no current water quality criteria for them. In Section 8 of the Panel's report (Science Advisory Panel and ADEC 2002), the Panel noted there were numerous studies mostly in freshwaters that were partially fed either by wastewater from treatment plants or runoff from confined animal feeding operations that detected a large number of different compounds at trace (parts per trillion) levels. The most frequently detected groups of these non-traditional pollutants were steroids, nonprescription drugs, insect repellant (DEET), and detergent metabolites. In terms of highest concentrations noted in most studies of publicly owned treatment works (POTW) wastes, detergent metabolites, steroids

Table 2
Maximum observed priority pollutant data from large cruise ships during the summer of 2000, compared to water quality criteria before and after a minimal dilution factor of 50,000

Priority pollutant	Alaska Marine Water Quality Standard (μg/L)	Maximum observed effluent concentration (μg/L)	Concentration after dilution factor of 50,000 (μg/L)
Carbon tetrachloride	50,000 (acute)	27	Negligible
1,2-Dichloroethane	113,000 (acute)	1.9	Negligible
Toluene	5000 (chronic)	5.1	Negligible
Tetrachloroethene	450 (chronic)	740	Negligible
Dibromochloromethane	6400 (chronic)	93	Negligible
Ethylbenzene	430 (acute)	4.7	Negligible
Bromoform	3600 (h.health)	170	0.004
Phenol	5800 (acute)	250	0.005
1,3-Dichlorobenzene	1970 (acute)	380	0.008
1,4-Dihlorobenzene	1970 (acute)	350	0.007
1,2-Dichlorobenzene	1970 (acute)	390	0.008
2-Nitrophenol	4850 (acute)	5.4	Negligible
Naphthalene	2350 (acute)	3.0	Negligible
2,4,6-Trichlorophenol	65 (h. health)	3.2	Negligible
Dimethylphthalate	3.4 (chronic)	1.1	Negligible
Acenaphthene	710 (chronic)	7.7	Negligible
4-Nitrophenol	4850 (acute)	8.0	Negligible
Diethylphthalate	3.4 (chronic)	27	0.0005
Di-*n*-butylphthalate	3.4(chronic)	20	0.0004
Fluoranthene	16 (chronic)	1.2	Negligible
Cadmium	9.3 (chronic)	0.35	Negligible
Chromium (total)	50 (chronic for hexavalent)	53	0.001
Copper	2.9 (acute)	7100	0.14
Nickel	8.3 (chronic)	630	0.01
Zinc	86 (chronic)	1800	0.036
Lead	5.6 (chronic)	250	0.005
Mercury	0.025 (chronic)	0.67	0.00001
Silver	2.3 (acute)	7.5	0.0001
Cyanide	1.0 (chronic)	73	0.005

and plasticizers were the three categories that stood out from the others. Cruise ship wastewaters may be expected to contain the same non-traditional compounds as POTWs, but compared to POTWs on a mass-balance basis, the contributions of these chemicals to the environment by cruise ships has to be relatively minor in extent. The Panel also understood that the mixing behind moving cruise ships was much greater than for POTWs and other sources discharging to freshwater streams and rivers.

7. Dilution and whole effluent toxicity test results

There was a request from a member of the public to the ADEC to evaluate the toxicity of cruise ship effluents by the use of bioassay testing. The Panel recognized that because of the rapid dilution, such tests probably were not needed, but still recommended a limited testing program in order to answer the concern.

The use of bioassays in testing effluents is called whole effluent toxicity (WET) testing. WET testing typically involves acute and chronic bioassays conducted with a dilution series, to calculate either a no observed effects concentration (NOEC) or a point estimate of an effect such as a lethal concentration to 50% of tested organisms (LC_{50}). Dilution series for land-based point sources typically look at a progression that decreases by a factor of 2, such as 50%, 25%, 12.5%, 6.25% and 3.125% effluent. Because moving cruise ships have much greater initial dilution, the Panel recommended a dilution series that decreased by a factor of 10 (50%, 5%, 0.5%, 0.05%, 0.005% and 0.0005% effluent). Acute marine bioassays were run using mysids (shrimp) and topsmelt (fish). Chronic bioassays were run using a bivalve larvae test and an echinoderm fertilization test. A review of the 2002 WET testing data was presented as Appendix 8 in the Panel's report (Science Advisory Panel and ADEC 2002).

The WET test results were interesting. One sample came from a vessel that used a reverse osmosis treatment system, and there were no acute or chronic effects at the highest effluent concentration tested (50%). Another sample was a black water sample from a small cruise ship that used a macerator/chlorinator system that was obviously not working at the time the sample was drawn. That sample also exhibited no acute or chronic effects at the highest effluent concentration tested (50%). Other test results had acute NOECs varying from 50% to 0.5% effluent and chronic NOECs varying from 5% to 0.05%. The lowest chronic NOEC was equivalent to an effluent after a dilution factor of 2000.

Excessive residual chlorine concentrations (16,200 μg/L and 30,300 μg/L) in two of the effluents appeared to explain the WET results for the samples that exhibited the most toxicity.

Acute or chronic toxic effects on marine organisms are not expected at the high dilutions that occur when vessels are underway. ADEC designed the 2003 WET tests to determine if there were any negative effects to the marine environment during stationary discharges when the dilution factor would be low. The effluent concentrations used for the 2003 WET tests decreased step-wise by a factor of 2, similar to concentrations typically used for land-based point sources. ADEC calculated stationary dilution factors for each ship during a worst case neap tide (lowest tidal range and tidal currents) scenario. The acute NOECs ranged from 50% to 12.5% effluent. The chronic NOECs ranged from 50% to less than 1.5%. The large cruise ship specific dilution factors indicate that large cruise ships' wastewater effluent will not cause toxicity in receiving waters even during stationary discharge. Stationary wastewater discharge from small cruise ships may cause toxicity.

8. Dilution and bacteria

Section 3 of the Panel's report (Science Advisory Panel and ADEC 2002) evaluated bacteria data. The relevant scenarios of exposure to large cruise ship discharges include secondary contact recreation by fishermen, kayakers, and motor powered watercraft, such as jet skis crossing a cruise ship wake shortly after passage of the cruise ship, and raw shellfish consumers harvesting shellfish along the shoreline. The applicable standards for these two situations include the following:

- Secondary recreation, defined in Alaska water quality regulations as recreation activities in which water use is incidental, accidental, or sensory, including fishing, boating, camping, hunting, and hiking. The applicable bacteria standard is 200 fecal coliform (FC) per 100 mL as a geometric mean for samples over a 30-day period with no more than 10% of the samples exceeding 400 FC/100 mL.
- For harvesting of raw mollusks or other raw aquatic life for human consumption the applicable standard is based on a 5-tube decimal dilution test, the median most probable number (MPN) may not exceed 14 FC/100 mL, and not more than 10% of the samples may exceed a median MPN of 43 FC/100 mL.

During the Summer 2000 monitoring season, 94 black water, 81 gray water and 11 combined black and gray water samples taken from 21 different large cruise ships were analyzed for fecal coliform bacteria. The geometric mean of the effluent data was 5460 FC/100 mL, the median was 27,500 FC/100 mL and the range of values was from less than 2 to more than 32,000,000 FC/100 mL. Gray water bacteria levels were often as high as black water.

Appendix 7 of the Panel's report included a spreadsheet with all the bacteria data, showing the effluent concentrations, and the concentrations after dilution factors of 50,000, 500,000 and 5,000,000. A dilution factor of 50,000 is considered to be a minimal dilution to which someone might be exposed when engaged in secondary recreation activities in the wake of a cruise ship that was discharging. A dilution factor of 5,000,000 is considered to be a minimal dilution by the time any effluent discharged more than a nautical mile from land might approach the nearest shore when onshore winds existed. The Panel concluded that the dilution factor of 5,000,000 was conservative for bacteria since a number of other processes also affected bacterial numbers (e.g. consumption or die-off, in the water column). Table 3 presents a summary of the bacteria data information (geomean, median, % greater than 400 and % greater than 43) of the Summer 2000 data for comparison to the applicable standards.

The available data coupled with the relevant dilutions, indicate that violations of the applicable bacterial water quality standards were not predicted to occur for any of the relevant exposure scenarios from the summer 2000 bacteria data set.

The State of Alaska and the Federal Government have established new regulatory limits for bacteria in gray water and black water discharges from large cruise ships equal to the secondary contact recreation standard. These regulations also require that a vessel must be at least one nautical mile from shore and travel at 6 knots or greater (unless they have a very high level of treatment in which case they may discharge continuously, even in port) In 2004, Alaska changed its approach to small passenger vessel wastewater effluent management. Emphasis has moved away from adherence with bacteria limits to Best Management Practices that eliminate or reduce stationary wastewater discharge (2004 Alaska House Bill 522).

Data from the summer 2001 involved fewer large cruise ships (11) and fewer samples. Twelve of the combined black and gray water samples from 2001 were from ships providing new advanced treatment and four were from an MSD system. The summer 2001 data set had a geometric mean of 1.6 FC/100 mL, a median of 1 FC/100 mL and less than 10% exceeded 43 FC/100 mL. Hence without dilution, the tested combined black and gray water effluents met the most stringent bacteria water quality standard. In compliance with the state's requirements, no vessels discharged untreated black water in the state's waters, and either provided advanced treatment or discharged more than 3 nautical miles offshore. The gray water tested in the summer of 2001 did not yet require advanced treatment and bacterial levels observed were similar to gray water from the summer of 2000.

The regulatory limit is applied directly to the large cruise ship discharge, without any consideration of the dilution attained by the 6 knot—1 nautical mile distance requirement. The Panel's evaluation of the Summer 2000 data set was based on the mixing conditions that occur under the same minimal constraints of discharge at 6 knots and one nautical mile from shore as required in the new regulations. The technology forcing standard was imposed before the Panel's report was completed. The analysis by the Panel shows that as long as discharges were at speeds greater than or equal to 6 knots and at least 1 nautical mile from the shore, the water quality standards were met and there was not a water quality reason to impose the Alaskan technology standard for bacteria.

Cruise ship discharges of bacteria should be considered within the context of a background of fecal coliform from all land-based sources. There will be a number of different sources to the nearshore bacteria that will produce significant exceedances of the standards, and the focus on offshore discharges from cruise ships does not address the real problems.

Table 3
Summary statistics for all bacteria data from Summer 2000 after applying dilution factors (DF)

	Geomean	Median	%>400	%>43
DF 50,000	5.46	27.5	2	20
DF 500,000	0.55	2.75	0	2
DF 5,000,000	0.05	0.28	0	0

Geometric mean and median values are in FC/100 mL.
Alaska's standard for secondary contact recreation was met with the dilution factor of 50,000. Alaska's raw shellfish consumption standard was met with a dilution factor of 500,000.

9. Dilution and nutrients

The limiting nutrient for phytoplankton growth in Southeast Alaska marine waters is dissolved nitrogen. From effluent nutrient data collected in the summers of 2000 and 2001, the maximum mean total nitrogen concentration in large cruise ship wastewater discharges was estimated to be 5 mmols (5 mM) or 0.07 mg/L. By applying a minimum mixing factor of 50,000, the wastewater total nitrogen concentrations after the initial rapid mixing are one-tenth to one-hundredth of the lowest Alaska marine water background concentration, or about 0.1 μmol (μM). This amount of nitrogen can be converted to a very small amount of phytoplankton over the next several days, approximately 0.03 μg of chlorophyll per liter. This amount of chlorophyll is only a hundredth to a thousandth of the naturally existing phytoplankton, and for computational purposes, is treated as if it stayed in the relatively small volume of water of initial mixing. The computation does not mean that there would be an increase of 0.03 μg per liter of chlorophyll to all the surface waters. Essentially, given the initial rapid dilution, and subsequent dilution, the discharged water will have little impact on the natural nutrient cycle.

10. Summary

The following simple equations may be used to conservatively describe dilution of wastewater discharges from moving large and small cruise ships.

10.1. Large cruise ship

$$\begin{aligned}\text{Dilution factor} &= 4 \times (\text{ship width} \times \text{ship draft} \times \text{ship speed}) \\ &\quad /(\text{volume discharge rate}) \\ &= 4 \times (\_\_\_\text{m} \times \_\_\_\text{m} \times \_\_\_\text{m s}^{-1})/(\_\_\_\text{m}^3\ \text{s}^{-1})\end{aligned}$$

10.2. Small cruise ship

$$\begin{aligned}\text{Dilution factor} &= 3 \times (\text{ship width} \times \text{ship draft} \times \text{ship speed}) \\ &\quad /(\text{volume discharge rate}) \\ &= 3 \times (\_\_\_\_\text{m} \times \_\_\_\_\text{m} \times \_\_\_\_\text{m s}^{-1})/(\_\_\_\_\text{m}^3\ \text{s}^{-1})\end{aligned}$$

The effects of dilution on toxicant data, whole effluent toxicity test results, bacteria data and nutrient data based on effluent data obtained before the vessels came under the new Alaska discharge standards for cruise ships, demonstrated that black water and gray water discharges from cruise ships would not have resulted in exceedances of water quality standards, provided the ships were traveling at speeds of 6 knots or greater, and were at least 1 nautical mile from shore. The Panel's final report[5] is available online.

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[5] Science Advisory Panel and ADEC 2002.