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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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[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