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Is the aquatic environment sufficiently protected from chemicals discharged with treated ballast water from vessels worldwide? – A decadal environmental perspective and risk assessment

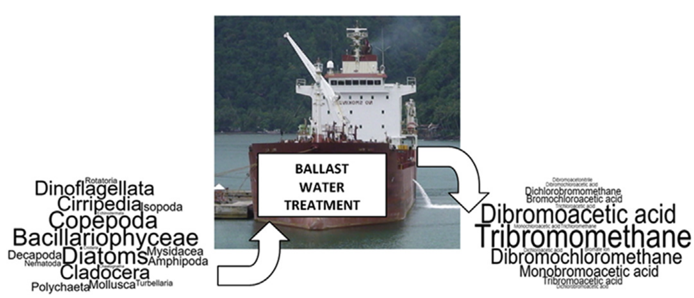
Matej David [a, b, *], Jan Linders [c], Stephan Gollasch [d], Jan David [a]

[a] Dr. Matej David Consult, Korte 13e, 6310 Izola, Slovenia
[b] Faculty of Maritime Studies, University of Rijeka, Croatia
[c] De Waag 24, Amersfoort, 3823 GE, the Netherlands
[d] GoConsult, Grosse Brunnenstrasse 61, 22763 Hamburg, Germany

HIGHLIGHTS

- Data regarding ballast water discharges of 42 ballast water management systems were studied.
- Active substances, disinfection byproducts, and neutralizers were summarized.
- Most of these substances may not cause unacceptable risk to the receiving environments.
- Some relevant and other chemicals risk reached levels of concern.
- Recommendations are provided to improve the risk assessment and approval process.

GRAPHICAL ABSTRACT



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ABSTRACT

Ballast water managements systems (BWMS) installed on vessels may use active substances to inactivate or kill organisms in the ballast water. This paper provides new insights in this global issue - discharge of hazardous disinfection by-products with ballast water and related risk assessment for the environment. Considering the possible extent of this issue, the International Maritime Organization (IMO) engaged the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP)-Ballast Water Working Group (BWWG) to oversee the evaluation process of BWMS that make use of active substances to prevent negative effects. We analysed all BWMS that received IMO final approval over a decade until 2017 and provide an overview of active substances used for ballast water treatment and disinfection by-products in the discharged ballast water. A risk assessment was conducted using the GESAMP-BWWG methodology for two very different commercial ports (Koper, Slovenia and Hamburg, Germany). Some relevant chemicals (chloropicrin, monochloroacetic acid, and dibromoacetonitrile) and other chemicals (isocyanuric acid and sodium thiosulphate) reached levels of concern, indicating a risk for aquatic organisms after discharge of that ballast water. From this analysis, it became clear GESAMP-BWWG worst-case scenario assumptions do not fully account for the potential environmental risks. We

* Corresponding author. Dr. Matej David Consult, Korte 13e, 6310 Izola, Slovenia
E-mail addresses: matej.david@siol.net (M. David), jbhj.linders@gmail.com (J. Linders), sgollasch@gmx.net (S. Gollasch), jan.david@siol.net (J. David).

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provide recommendations how to make this risk assessment more robust, recommend further research, and urge for policy as well as regulatory responses.

1. Introduction

Commercial vessels fundamentally depend on the use of ballast water for their safe operations as a function of their design and construction. Global ballast water discharges from vessels engaged in the international seaborne trade have been estimated as 3.1 billion (3.1×10^9) tonnes per year (David, 2015). When water is loaded as ballast from a vessel's surrounding environment, suspended matter and living organisms are also taken on board. When those are released in some of the next ports, several organisms can survive. Numerous cases of transferred species which caused harmful effects on human health, the natural environment, and the economy are known. Some transferred species caused disastrous, and irreversible impacts to the recipient environments (e.g., Hallegraeff and Bolch, 1991; Pimentel et al., 2005; Gollasch, 2006; Vila et al., 2010). Noting these unwanted impacts, a globally unified response was provided with the *International Convention for the Control and Management of Ships' Ballast Water and Sediments, London 2004*, (BWM Convention) (IMO, 2004) which entered into force on 8 September 2017 (IMO, 2016).

The BWM Convention requires vessels to conduct ballast water management (BWM) to meet the D-2 standard, which is a numerical, biological standard setting limits on viable organism concentrations in the ballast water discharge (IMO, 2004). It was recognized that the required viable organism discharge limits may only be achieved by some kind of ballast water treatment (Lawrence and Cordell, 2010; Werschkun et al., 2014; Casas-Monroy et al., 2015). Different water treatment technologies are used in BWM systems (BWMS), which are mostly a combination of mechanical, physical, and chemical processes to eliminate or inactivate organisms in the ballast water (Tsolaki and Diamadopoulos, 2010; Yamada et al., 2013; Balaji et al., 2014; David and Gollasch, 2015; Feng et al., 2015; Dang et al., 2016; Sun and Blatchley, 2017; Ren, 2018).

All BWMS need to go through an approval process conducted according to International Maritime Organization (IMO) guidelines (IMO, 2008a), which were recently revised and made mandatory (IMO, 2018). When active substances (AS), e.g., chlorine, ozone, are employed in the treatment process, it is a concern that residual chemicals may remain after the process and then be discharged into the environment (Werschkun et al., 2012, 2014; Fisher et al., 2014; Zhang et al., 2014; Culin and Mustac, 2015; Shah et al., 2015; Heeb et al., 2017; Xue et al., 2017). To ensure for human health and environmental safety, BWMS making use of AS are evaluated by an additional process of basic and final approval (FA) conducted by the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP)-Ballast Water Working Group (BWWG) (Bowmer and Linders, 2010). This evaluation is done according to the IMO Procedure for approval of ballast water management systems that make use of active substances (G9) (IMO, 2008b) and the GESAMP-BWWG methodology (IMO, 2017).

At present more than half of the BWMS that have been approved for use on vessels make use of AS (David and Gollasch, 2015; IMO, 2015a). Considering the large volumes of ballast water discharged in ports around the world, this becomes a critical subject. In the type approval process of each BWMS that makes use of AS, land-based tests are conducted to identify the chemicals and their concentrations in the ballast water, and a quantitative risk assessment (RA) is then conducted using a simulated port scenario (IMO, 2017). Until now there was only one similar study, conducted by Zhang et al. (2014), to address RA for some chemicals discharged in treated ballast water for Tianjin Harbour, China. However, their study was based on only one laboratory-scale BWMS.

In this paper we identified the AS, the residual chemicals discharged with ballast water, their concentrations, and their risks for the environment associated with 42 BWMS that received IMO final approval (FA) in the decade 2007 to 2017. We further conducted environmental RA applying the chemical data to port situations of two multipurpose ports, the Port of Koper, Slovenia and the Port of Hamburg, Germany. We applied and discussed some aspects of the GESAMP-BWWG methods used in the BWMS evaluation process. The methods developed here and chemical data used may also be applied to study any other port worldwide, as well as to improve the robustness of methods and processes used in the RA for this purpose.

2. Materials and methods

2.1. BWMS and relevant chemicals data

We reviewed and analysed the data from all BWMS non-confidential FA dossiers and GESAMP-BWWG reports on AS and residual chemicals discharged with ballast water until and including 2017 (see Supplementary data, BWMS references). The GESAMP-BWWG methodology (IMO, 2017) was used for the selection of residual chemicals and for the characterisation of risks to the environment. According to IMO (2017), 41 chemicals are most commonly associated with treated ballast water, 39 of those are termed Relevant Chemicals (RC), one is an AS (sodium hypochlorite), and another belongs to Other Chemicals (OC) (the neutralizer sodium thiosulphate). The following substance definitions were used (IMO, 2017): a) AS means a substance or organism, including a virus or a fungus, that has a general or specific action (chemical or biological) on or against harmful aquatic organisms and pathogens; b) RC means transformation or reaction product that is produced during and after employment of the ballast water management system in the ballast water or in the receiving environment and that may be of concern to the ship's safety, aquatic environment and/or human health; and c) OC means any other substance, other than the AS(s) or RC(s), potentially associated with the system either intentionally or resulting from the treatment of ballast water.

The ratio of the Predicted Environmental Concentration (PEC) and the Predicted No Effect Concentration (PNEC) (=PEC/PNEC) was used for the risk characterisation. If the PEC/PNEC is below 1, no unacceptable risks for the environment may be expected (IMO, 2017).

The highest concentration of RCs and OCs that was determined during the development of all BWMS were identified. Data have been arranged in a spreadsheet and were analysed for the frequency of each chemical identified, their minimum and maximum concentrations. Median, mean and standard deviations were calculated to provide an overview of the presence of chemicals in discharged ballast water from BWMS that make use of AS. The mean concentrations identified were used to calculate the PEC max