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An evaluation of cumulative risks from offshore produced water discharges in the Bass Strait

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ABSTRACT

Chemical analyses and toxicity testing using six marine species were used to characterize the hazard of produced waters (PW) to marine life from twelve Australian offshore platforms. Hazard data were used in conjunction with platform-specific plume discharge dilution and species sensitivity distribution modeling to estimate cumulative risks by calculating the multiple substance potentially affected fraction of species in the local marine environment. Results provided two independent lines of evidence demonstrating that cumulative risks to marine life from these discharges meet intended 95% species protection goals at the edge of the mixing zone. A limited number of PW constituents (hydrocarbons, sulphide and ammonia) appeared to dictate risk thereby informing management and providing a rationale for more targeted analyses in future monitoring studies. Based on these findings a tiered framework is proposed to foster consistent screening and potential refinement of cumulative risk evaluations for PW discharges.

1. Introduction

The Bass Strait is located off the southeastern coast of Australia separating the mainland state of Victoria from the island of Tasmania. This marine waterway links the Tasmanian Sea to the east and the Indian Ocean to the west. During the 1960s significant offshore oil and gas resources were discovered in the Gippsland Basin below the relatively shallow waters (< 100 m) in the eastern area of the Bass Strait. Subsequent production has proved the importance of this resource in transforming Australia's industry and economy. This resource asset is expected to continue to supply society with vital energy for decades to come (ExxonMobil, 2016b). The Bass Strait is also home to wide range of endemic marine life, and both commercial and recreational fisheries (Lavering, 1994). Past studies have concluded that the environmental impacts of oil and gas exploration and production operations in this region are minor and localized (ISRC, 1993). These findings are consistent with the more recent review by Bakke et al. (2013) that focused on the Norwegian offshore petroleum sector.

To provide continued protection of the environment and comply with regulatory requirements, oil and gas titleholders must prepare environment plans that document the interaction of offshore activities with the marine environment. A key element of these plans is to demonstrate that adequate measures have been implemented to reduce environmental impacts and risks to as low as reasonably practicable (ALARP) and acceptable levels (NOPSEMA, 2016). It should be noted that in some cases, interactions among infrastructure and local ecology can convey benefits. For example, pipelines on the seabed floor have been shown to provide preferred foraging habitat for Australian fur seals (Arnould et al., 2015). Platforms can also host considerable populations of teleost fish and other species (Neira, 2005; Pradella et al., 2014).

An important environmental aspect of offshore production operations is the discharge of produced water (PW) that is generated as a by-product of resource extraction (Scholten et al., 2000). PW is typically discharged continually over the lifespan of the asset, which may span decades. While pre-treatment of PW is performed before release to the marine environment, this effluent may contain a variety of residual inorganic and organic contaminants that can pose toxicity concerns to marine life. The sources of these contaminants can be geogenic in nature (i.e. derived from the formation) or be intentionally introduced in operations. Example geogenic contaminants include metals, ammonia, sulphide, cyanide, hydrocarbons and phenols, some of which are residual from the process of separating oil and water from the petroleum reservoir. Chemicals used to facilitate separation of oil and gas from water or prevent hydrate, corrosion or scale formation to ensure reliable and safe production may also be released (Kelland,

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2014). However, unlike geogenic constituents that represent an ongoing source of contaminants to the local marine environment, production chemicals are often transiently used and managed by purposeful selection of low hazard substances. Recent trends over the last decade show significant progress in applying systematic hazard evaluations of production chemicals to reduce the use and marine discharge of more hazardous substances (La Védrine et al., 2015).

A practical challenge for offshore operators is to document that control measures are in place to ensure environmental impacts and risks of PW discharges are reduced to ALARP and acceptable levels. While some methods to support this evaluation are usually prescribed (such as monitoring of oil-in-water concentrations), practical, cost-effective approaches that are transparent and reflect advances in risk assessment with associated measurement criteria are needed. Several approaches for risk evaluation of PW discharges may be considered. One risk assessment strategy is to couple analytical characterization of specific PW constituents to dilution modeling of PW plumes in the local marine receiving water to provide conservative estimates of resulting exposures. Predicted exposure concentrations for individual contaminants can then be compared to corresponding water quality objectives that are intended to protect marine life (Zhao et al., 2008; Beyer et al., 2012). The Australian and New Zealand Environment Conservation Council have published water quality guidelines that can be used in this context for performing screening risk assessments of specific PW contaminants (ANZECC, 2000a). The ANZECC guidelines were derived using species sensitivity distributions (SSDs) based on empirical toxicity data compiled on marine test species for each contaminant. The ANZECC guidelines recognize that different levels of protection may be appropriate depending on the disturbance history and perceived conservation value of the ecosystem. Two different levels of protection for each contaminant are generally specified as concentrations that are intended to protect a 99% and 95% species for unmodified systems and slight to moderately disturbed systems, respectively. In the absence of site-specific data, the guideline values are not used as pass or fail criteria but rather regarded as trigger values which, if exceeded, may initiate further risk evaluation. One disadvantage of this approach is the limited number of relevant marine ANZECC guideline values that are available for PW contaminants and the outdated nature of the underlying toxicological data used in establishing the values currently available. A second limitation is that screening risk evaluation of individual contaminants ignores the potential cumulative risks posed by simultaneous exposure to the multiple contaminants present in PW.

A second alternative approach involves direct toxicity assessment (DTA) of PW (van Dam and Chapman, 2001; Adams et al., 2008). In this approach, various marine test organisms are exposed to sequential dilutions of PW in clean seawater to evaluate mortality as well as other acute or chronic sub-lethal endpoints. The results of these tests are expressed in terms of the PW dilution that corresponds to a given degree of effect (e.g. 10%, 50% response) for the endpoint being investigated. DTA results can be converted into toxic units (TUs) to conveniently express the magnitude of the observed PW toxicity:

$$TU_{DTA,j} = \frac{100\%}{L(E)C_{R,j}} \quad (1)$$

where $L(E)C_R$ denotes the lethal or effective concentration expressed as percent of diluted PW that causes a R% adverse effect on species j. For example, a 48 h EC_{10} = 4% indicates that a 25 fold dilution of the PW sample causes a 10% response for the test organism/effect endpoint investigated after 48 h exposure to diluted PW. Results of DTA can also be used to calculate a potentially affected fraction that is associated with the multiple substances present in the PW sample (De Zwart and Sterkenburg, 2002):

$$msPAF_{DTA,z} = \frac{1}{1 + exp(-[Log\,(TU_{DTA}) - Log\,(DF_z)]/\beta_{DTA})} \quad (2)$$

where $Log\,(TU_{DTA})$ represents the mean of log transformed PW toxic units obtained from toxicity tests results with different marine test species for a given PW source (e.g. platform), β_{DTA} is a scale parameter that defines the SSD shape and is calculated as:

$$\beta_{DTA} = \frac{\sqrt{3}}{\pi}\beta_j \quad (3)$$

where β_j is the standard deviation of the log transformed TU dataset for platform j and DF_z = average dilution factor at distance z from the discharge release. Using this approach a calculated $msPAF_{DTA} < 0.05$ calculated using TUs derived from chronic toxicity tests obtained on multiple marine species would indicate compliance with water quality objectives and thus acceptable risk consistent with a recommended 95% species protection goal (ANZECC, 2000b).

A key advantage of the DTA approach is that the bioavailability and interactions of known and unknown substances are quantitatively taken into account. A significant limitation is the time and cost in conducting these tests across multiple marine test species and effect endpoints. A further potential drawback is the relative precision of PW toxicity tests compared to routine chemical analysis and the larger volumes of samples that need to be collected and shipped from offshore facilities. DTA also fails to identify which PW constituents are driving the observed toxicity. To address which constituents are causally related to toxicity, further DTA studies using toxicity identification evaluation procedures are required that add further cost and animal use (van Dam and Chapman, 2001).

A third framework to evaluate PW risk relies on applying toxicity modeling to multiple contaminants to predict a multiple substance potentially affected fraction of species that would be adversely impacted (Schäfer et al., 2013; Posthuma et al., 2016). This method generally involves two steps (Traas et al., 2002; De Zwart and Posthuman, 2005; Olmstead and LeBlanc, 2005). In the first step, mixture constituents expected to share a common toxicological mode of action (TMoA) are assumed to exert effects based on simple concentration addition. This involves the application of toxic units (TUs) which are calculated by dividing the predicted exposure concentration of each substance that contributes to a given TMoA by the corresponding concentration causing toxicity that reflects the median species

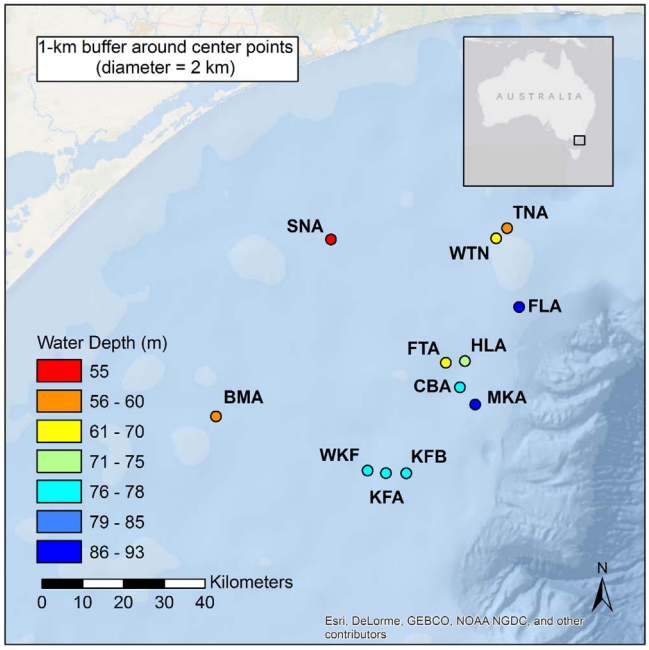

Fig. 1. Location of twelve offshore platforms investigated in this study. Each platform is designated by a three letter abbreviation as indicated in Table 1. Symbol color denotes ocean depth. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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