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Research article

The science-policy interface of risk-based freshwater and marine management systems: From concepts to practical tools

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ABSTRACT

Maintaining the current state of ecosystem services from freshwater and marine ecosystems around the world is at risk. Cumulative effects of multiple human pressures on ecosystem components and functions are indicative of residual pressures that “fall through” the cracks of current industry sector management practices. Without an understanding of the level of residual pressures generated by these measures, we are unlikely to reconcile the root causes of ecosystem effects to improve these management practices to reduce their residual pressures. In this paper, we present a new modelling framework that combines a qualitative and quantitative assessments of the effectiveness of the measures used in the daily operations of industry sectors to predict their residual pressure that is delivered to the ecosystem. The predicted residual pressure can subsequently be used as an input variable for ecosystem models. We combine the Bow-tie analysis of the measures with a Bayesian belief network to quantify the effectiveness of the measures and predict the residual pressures.

1. Introduction

The interface between science and policy eventually needs to operationalize ecosystem-based approaches to management (Gavaris, 2009; Murawski, 2007; Cormier et al., 2017) so as to carry into effect policy objectives. Formalizing and defining the science-policy interface within a management system or even among management systems is a key challenge in achieving sustainable development while maintaining the current state of ecosystems (Creed et al., 2016; Gluckman, 2016). Human activities and their demands for ecosystem services generate pressures that can cause physical changes, chemical interferences as well as biological and ecological disturbances within marine and freshwater ecosystems (Halpern et al., 2008; Allan et al., 2013). Cumulative effects assessment has been the hallmark approach to unravel the complex pressure-effect relationships and inform mitigation strategies to reduce them (Ban et al., 2010; Andersen et al., 2015; Jones, 2016; Stelzenmüller et al., 2018). However, mitigation strategies are most often focused on reducing the effects (Mangano and Sarà, 2017) and seldom consider or integrate an assessment of the effectiveness of the management measures implemented to reduce the pressures at their sources (Katsanevakis et al., 2011; ICES, 2014; Elliott et al., 2017).

One strategy for identifying how pressures are managed is by analysing the management system of policies, processes, and procedures that are implemented to reduce the pressures (ISO, 2009). Performance of such a system is a measure of the degree to which policy objectives are being achieved (ISO, 2005) such as the effectiveness of current mitigation strategies in reducing environmental effects (Batista et al., 2015). In addition to compliance and external factors (Girling, 2013; Green, 2015), performance relies significantly on the effectiveness of so called operational controls (e.g. procedures, tasks, maintenance, repairs) that are implemented in the daily operations on the ground (Anthony and Dearden, 1980). In this operational context, effectiveness is the extent to which controls can produce their expected result or outcome. Lack of performance could be attributed to either the effectiveness of the controls or the legislation and policies that are intended to regulate the phenomenon in question (Cormier et al., 2017). For example, best management practices that are meant to reduce sediment input to watercourses are designed to operate effectively within certain

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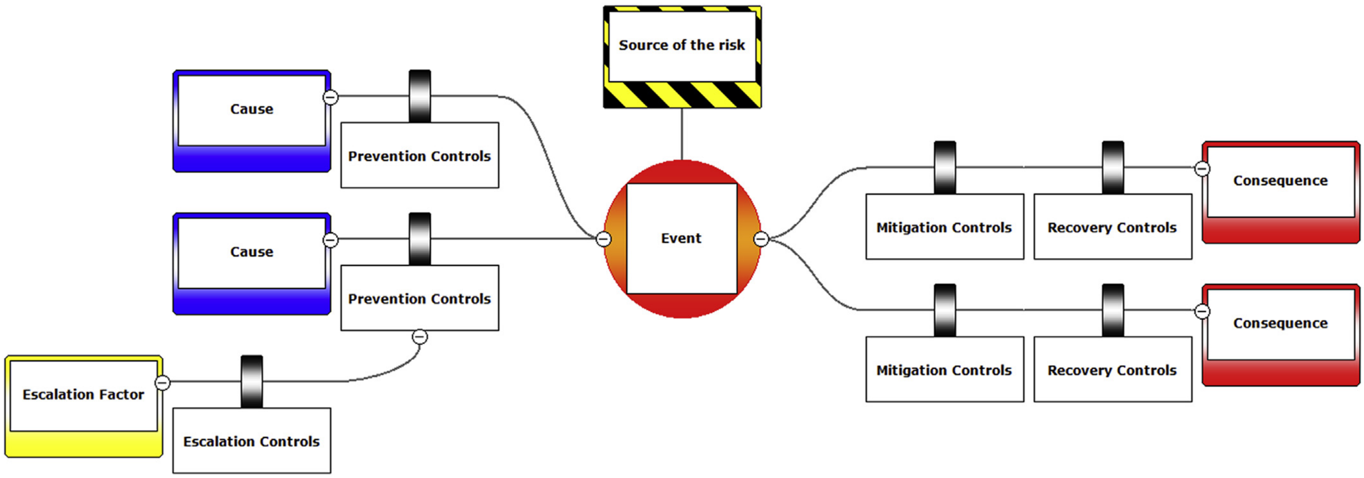

Fig. 1. Bow-tie structure (BoxTieXP adaptation of IEC/ISO 31010).

boundary conditions (Cooke et al., 2015). Thus, despite proper installation and maintenance, residual amounts of sediment still reach the watercourse. Based on the effectiveness of a given control design, we are of the view that the collective residual materials, substances or wastes released to the environment can represent significant pressures to sensitive aquatic ecosystems. This implies that controls implemented as regulatory requirements or best management practices are inadvertently contributing to cumulative environmental effects despite the requirements and objectives stipulated in legislation and policy (Sardà et al., 2014; Jones, 2016; Cormier et al., 2017).

Outside the influence of natural or climate driven processes, we call 'residual pressures' the pressures that are generated by the residual materials, substances or wastes as a result of the level of effectiveness of the controls that are implemented in the daily operations of industry sectors. Without the capability of estimating the level of the residual pressures, we are unlikely to reconcile the root causes of disturbances to ecosystems with the management practices for addressing those disturbances and ultimately, the performance of their management systems in achieving environmental objectives. We use the Bow-tie analysis (IEC/ISO, 2009) and a Bayesian Belief Network (Badreddine and Amor, 2013) as an approach to predict the residual pressure. This approach provides a predicted residual pressure that would serve as an input variable to ecosystem models. In this paper, we tested this approach in two distinct case studies being 1) nutrient loading in the Great Lakes, and 2) sea-floor integrity of the North Sea. Based on these two case studies, we identify knowledge and data gaps and reflect on lessons learned from implementing such an approach.

2. Materials and methods

We use the Bow-tie analysis to develop a qualitative model of the controls implemented to reduce a pressure generated from the activities of multiple sectors. We then use a Bayesian belief network model (Marcot et al., 2006) to predict the residual pressure based on the integration of the effectiveness of each control, the implementation compliance of the controls and external factors that could undermine the effectiveness of the controls. Here, we are using the predicted residual pressure as an indicator of the effectiveness of the management system of controls implemented to reduce an initial pressure instead of predicting the ecosystem effects. A description of the data manipulation, model application and predicted total residual pressure loads for the two case studies are provided in the Supplementary Material section.

In the case study for the Laurentian Great Lakes, the analysis is conducted on farming best management practices implemented to reduce phosphorus as a result of their activities. The case study was conducted within the boundaries of the Grand River Watershed of Lake Erie considered as a priority area for enhanced management of phosphorus. The Bow-tie analysis identified the sequence of controls of each farming practice implemented to reduce and prevent phosphorus from reaching Lake Erie. Based on the Bow-tie structure of the controls, a Bayesian belief network was developed to quantify the effectiveness of each control and predict the residual amount of phosphorus that could potentially reach Lake Erie.

In the case study for the North Sea, the analysis was conducted on marine spatial management controls implemented to reduce abrasion and selective extraction of the seafloor as a result of fish trawling, aggregate mining, gas extraction, and anchoring. The case study was conducted within the boundaries of the German Exclusive Economic Zone given that bottom trawling is considered as causing significant impact on the demersal ecosystem. The Bow-tie analysis was used to identify the controls that restrict fishing activities to reduce abrasion to the seafloor. The Bayesian belief network was then used to quantify the effectiveness of the fishing restrictions and predict the residual amount of abrasion in the German Exclusive Economic Zone.

2.1. Controls assessment technique: Bow-tie analysis

As one of the controls assessment techniques of IEC/ISO 31010 (IEC/ISO, 2009), the Bow-tie analysis is primarily a diagrammatic representation of the controls implemented within a cause-event-consequence pathway in the presence of a source of risk (Fig. 1). The technique was developed by the petrochemical industries to assess the prevention and mitigation measures needed to avoid catastrophic events as a result of a failure of their operational controls (Lewis and Hurst, 2005; Cockshott, 2005). The technique is currently used in wide variety of industries dealing with health and safety risks (Saud et al., 2014; van Thienen-Visser et al., 2014; Abimbola et al., 2014). In an ecosystem context, the technique has been adapted to the analysis of legislation and policies (Creed et al., 2016; Elliott et al., 2017; Kishchuk et al., 2018).

The basic structure of the Bow-tie identifies the causes of an event in the presence of a source of risk and the consequences of that event when it occurs. Prevention controls are intended to reduce the likelihood of an event; mitigation controls are intended to reduce the magnitude of the consequences of an event and recovery controls are used to recover from the consequences that could not be mitigated. Escalation factors are external factors that can undermine the effectiveness of any of the prevention, mitigation or recovery controls. They require additional escalation controls to reduce the effects of the escalation factor on their effectiveness. This technique is a qualitative assessment of the prevention controls to prevent the event, the