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Regional Ecological Risk Assessment Using a Relative Risk Model: A Case Study of the Darwin Harbor, Darwin, Australia

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Abstract

There are many proposed and ongoing commercial, industrial and residential developments within the Darwin Harbor catchment in Northern Australia, to accommodate the projected population growth over the next 20 years. Hence, it is necessary to ensure the balance between these developments and ecosystem conservation. We evaluated ecological risk for the Darwin Harbor using a relative risk model (RRM). The catchment was divided into 22 risk regions based on small catchment boundaries and their homogeneity. Through the RRM, we ranked and summed the stressors and habitats within regions. The interaction between stressors and habitats were modelled through exposure and effect filters. The ecological assessment endpoints were maintenance of the mangrove health and the maintenance of water quality. The risk regions:
Myrmidon Creek, Blackmore River, Blesers Creek and Elizabeth River showed the highest total relative risk for ecological assets. These risk regions had a high percentage cover of industrial, commercial, residential areas, diffuse entry points, and climate change effects. The Creek A, Sandy Creek, West Arm and the Pioneer Creek were the risk regions with lowest total relative risk scores. The RRM is a robust application that is suitable for a large geographic area where multiple stressors are of concern.

**Indexing terms:** Ecological risk assessment, Relative Risk Model, mangrove, water quality, Darwin Harbor
INTRODUCTION

Darwin Harbor, located in the Northern Territory, Australia is a large indented embayment with three main arms: East Arm, Middle Arm and West Arm. The Harbor is globally significant as a macro tidal environment with a tidal range of about 7 to 8 meters, and monsoonal climate with uniformly high temperatures and solar radiation (Metcalfe 2007). The Darwin Harbor shoreline is covered by the most floristically diverse, and one of the largest mangrove habitats in the Northern Territory (Lee 2003). These mangroves comprise 36 species out of the 50 species regarded as mangroves worldwide, and cover approximately 20, 400 hectares (Metcalfe 2007).

There are major development projects and associated activities around Darwin Harbor such as significant plans for population growth, industrial expansion, resource processing infrastructure, and consequent increases in shipping and dredging. These developments pose risks for the natural, cultural, aesthetic and recreational values of the Harbor, and need to be managed carefully. Currently the Darwin Harbor catchment is subject to multiple pressures and conflict of use resulting in a major challenge for the government, industry and the community in managing the Harbor environment (The Darwin Harbor Advisory Committee 2003). The catchment encompasses a range of distinctive and special environments. Hence, it is important for the Harbor and its catchment to remain biologically productive, and for the water quality and habitats to be protected.

The Northern Territory government undertakes water quality, and ecosystem monitoring and testing throughout Darwin Harbor region. One of the key requirements for environmental monitoring programs in Darwin Harbor is the ability to combine knowledge from different sources into a consistent environmental management framework that enables stakeholders to
make practical and sound management decisions. Due to the current situation, the natural resources of Darwin Harbor region are experiencing increasing pressure from the growing human population, and subsequent rural and industrial developments. For example, although water resources of Darwin Harbor region are considered to be in good condition, there are areas of concern where sewage outfalls and urban stormwater can impact on the quality of the receiving water. Further, the assimilative capacity of the Harbor and waterways to receive pollutants from point and non-point sources, other understanding about key ecological processes and their vulnerabilities are poorly known (Northern Territory Government 2010). Hence, the decision makers are interested in evaluating the likelihood that adverse ecological impacts may occur as a result of exposure to multiple stressors in the region.

The Northern Territory government and other agencies that are responsible for industrial developments around Darwin Harbor have initiated their own individual environmental risk assessment programs rather than a single combined approach. One example is the dredging program introduced by a liquefied natural and petroleum gas project (INPEX). The key part of the project is managing environmental impacts in order to preserve the health of Darwin harbor. Hence, its main objectives are to monitor and respond to impact on environmentally sensitive receptors from offshore dredging, and to understand likely impacts of sedimentation and dredging activities (INPEX 2013). However, there is no way to combine sedimentation effects from other industrial developments to this assessment. To our knowledge, there is no integrated regional ecological risk assessment approach for policy makers, community organisations, managers and investors to support more robust debate, and more transparent decision making regarding rural and urban developments for Darwin Harbor. Hence, to maintain the sustainability
of the Darwin Harbor ecosystem, a statistically sound, transparent, repeatable ecological risk
assessment approach is essential. This study is a significant contribution to the regional
ecological risk assessment of Darwin Harbor.

The traditional ecological risk assessment methods comprise of evaluating the interaction
of three components: stressor, receptor and response (Landis and Wiegers 1997). This is fairly
simple at a single contaminated site with only one stressor involved. To expand this to a regional
scale, the scale, complexity of the structure, and the regional spatial components such as sources,
habitats and impacts to the assessment endpoints must be considered (Landis and Wiegers 1997).
The relative risk model (RRM) evaluates multiple, dissimilar stressors simultaneously and
comparatively at a regional scale (Landis and Wiegers 1997; Wiegers et al. 1998). Although this
method was introduced to assess the risk of chemical stressors in the beginning, it has
successfully been introduced to analyse biological or ecological stressors (Colnar and Landis
2007; Moraes et al. 2002; O’Brien and Wepener 2012; Yu et al. 2014). For example, recently
Bartolo et al. (2012) assessed the ecological risk of Australia’s tropical rivers, and identified the
most significant threats to the ecological assets of the northern tropical rivers.

The objective of this study was to evaluate the relative risk to ecological assets of the
Darwin Harbor catchment. Therefore, the application is; (a) to identify the sources and habitats
in different locations of the Darwin Harbor catchment; (b) to rank their importance in each
location; (c) to integrate them to predict the relative risk levels; and (d) to assess the uncertainties
that may propagate through the modelling process.
DATA AND METHOD

Study area

The Darwin Harbor’s management area encompasses 3227 km$^2$, and extends from Charles Point in the west to Gunn Point in the east. This includes the estuarine areas and tributaries of Woods Inlet, West Arm, Middle Arm, East Arm, Howard River, Elizabeth River and the land that drains into these waterways. Hence, the catchments include the cities of Darwin, Palmerston, Cox Peninsula, and new cities of rural areas (Figure 1). The population was about 120900 in 2006, however, the predicted population by the Australian Bureau of Statistics as of 2021 is 184500 (Skinner et al. 2009).

Data input

The digital topographic data layers of land use and land cover (scale 1:20,000, produced in 2002) were used as a preliminary data source for this study. The urban and rural residential areas, and transport and communication features were updated using Google Earth satellite image acquired on 28th March, 2014. The digital 10K topographic data series was used to extract water features, for example streams, rivers and dams, in the region (Geoscience Australia 2002). Since rivers and streams are line features, we introduced buffer zones of 5 m and 2.5 m for rivers and streams respectively to form polygon features. These buffer distances were selected considering the average width of water features. The “waterbodies” data set was prepared combining streams, rivers, dams and other water features in the area. The digital elevation model produced from the Shuttle Radar Topography Mission (SRTM), with a spatial resolution of 30m, was used to analyse sub-catchment vulnerability to sea level rise. The recent reports published by the oil company - INPEX for the Darwin LNG (liquefied natural gas) plant include the statistics and
spatial distribution of areas that are going to be affected by increasing sedimentation based on
the onshore dredging (Senden et al. 2013). The statistics of nutrient loads and other suspended
solids were obtained from a report published by the Northern Territory government analysing the
pollutant load entering to Darwin Harbor due to urban and rural land-use (Skinner et al. 2009).
Unfortunately, we were not able to find point source data for the Ludmilla Creek catchment. The
Darwin Harbor sub-catchment boundaries were adopted from the Australian Collaborative Land
Use Mapping program (V5), and were used as initial data for risk regions.

Regional ecological risk assessment methods evaluate the interaction of three different
regional spatial components, which include: sources that release stressors; the habitat where the
receptors reside; and impacts to the assessment endpoints (Landis and Wiegers 1997). Stressors
can be derived from diverse sources, including available topographic data, reports, and expert
knowledge. Receptors are often linked to habitats. The interaction between these stressors and
habitats is explained in terms of ranked exposure values. The impact to the assessment endpoint
is explained through the ranked effects. According to Landis and Wiegers (1997), at a regional
level, the ranking of exposures and effects must be done considering the spatial and temporal
heterogeneity of them.

The method used in this study was similar to Landis and Wiegers (1997). First, the method
identified sources and their reflecting stressors, habitats, and ecological assessment endpoints.
Then the area was divided into sub-areas to be used as risk regions based on their homogeneity.
In this study, we considered sub-catchments and their homogeneity to define risk regions. The
stressors and habitats were ranked for each risk region. Finally, an ecological risk for each risk
region was calculated by quantitatively determining the interaction of stressors and habitats.
According to U.S. Environmental Protection Agency, there are three main phases for ecological risk assessment: problem formulation; risk analysis; and risk characterization (USEPA (US Environmental Protection Agency) 1998). Each phase is divided into sub phases as shown by Figure 2. They are discussed in greater detail in the proceeding sections.

**Problem formulation**

The problem formulation phase is a process that identifies the nature of the problem through existing data. The foundation for the problem formation is based on how well we understand the system we are investigating. We reviewed available literature, including reports published by the Northern Territory government analysing different aspects of health of the Darwin Harbor, the Darwin Harbor regional management plans, and consulted experts in the field (Bartolo et al. 2012; Brocklehurst and Edmeades 1994-1995; Darwin Harbor Regional Plan of Management 2003; Metcalfe 2007; NRETAS 2010a; 2010b; Senden et al. 2013; Skinner et al. 2009) for preparing a conceptual diagram to understand the current situation of the catchment. Varieties of anthropogenic factors have resulted in development pressure on Darwin Harbor catchment. Based on the information collected and the conceptual diagram, we identified the major sources of this pressure, and categorized them into different stressors. For example, the source “Agriculture” was categorized into the following stressors: cropping; horticulture; and aquaculture. The corresponding ecosystem response variables for stressors were identified accordingly. For example, one of the ecosystem response variables for cropping is influx of nutrients and chemicals.

The habitat defines where the receptors reside at a regional scale (Landis and Wiegers 1997). The habitats that were directly related to the health of the Darwin Harbor, and that had
spatial data available were selected for this study. Further, we referred to the values identified by various experts in the field, the percentage of land cover, vulnerability to urban pressure, and significance of ecosystems in the region to decide on habitats to be considered for this study. Sources and threats were also defined based on the prepared conceptual diagram. Special attention was given to the availability of spatial data.

At this stage, we examined the integration and usage of available information on sources, stressors and their characteristics, exposure opportunities, the ecosystem components potentially at risk, and ecological effects. Then, a conceptual diagram was prepared combining all information to summarise our understanding of the Darwin Harbor ecosystem. This aided in finalising the sources, stressors and habitats and their interactions that were included in the RRM.

Ecological Assessment endpoints

According to the USEPA (US Environmental Protection Agency) (1998), management goals are desired characteristics of ecological values that need to be protected. There are five key management goals identified by the Darwin Harbour regional plan of management (The Darwin Harbour Advisory Committee 2003). The first goal is to maintain a healthy environment. The outcomes to be achieved through this goal are; (a) improved understanding and knowledge of the region’s environment; (b) protection and enhancement of freshwater, estuarine and marine water quality; and (c) protection of the health and functioning of ecosystems and conservation of biodiversity. The third goal which is linked to this first goal is to encourage ecologically sustainable development through planning and management of future developments (The Darwin Harbour Advisory Committee 2003). The other three management goals are mainly related to the
conflicting uses of the Darwin Harbor region rather than the ecological values. Hence, we considered the above explained first and third management goals and their expected outcomes only to decide on ecological assessment endpoints.

Assessment endpoints are expressions of an environmental value that is to be protected (USEPA (US Environmental Protection Agency) 1998). Ecological related endpoints often help to sustain the natural structure, function, and biodiversity of an ecosystem. Hence, deciding on an assessment endpoint is the process of defining a goal for a risk assessment through an ecological entity and its attributes. However, there are two main steps involved when selecting ecological endpoints (USEPA (US Environmental Protection Agency) 1998). The first step is to select ecological values that are suitable for assessment endpoints. Therefore, the ecological relevance, vulnerability to potential stressors, and relevance to management goals were considered (Obery and Landis 2002; USEPA (US Environmental Protection Agency) 1998). The other step is to identify the specific ecological entity and the characteristics of these entities that required a protection. In that sense, the ecological assessment endpoints reflect management goals, and the ecosystem they represent.

The Darwin Harbor is a small estuary covered by one of the largest and most diverse areas of mangroves in the Northern Territory. The Harbor supports a range of estuarine, freshwater, and terrestrial environments. Although the catchment mostly comprises vacant Crown land, it also contains a mix of commercial, industrial and residential areas including Darwin, Palmerston and Cox Peninsula cities. There has been some excellent research and mangrove monitoring in Darwin Harbor to balance the ongoing industrial developments and the conservation. However, a significant knowledge gaps remain. For example, the report; “The mangrove forest of Darwin
Harbour” by Moritz-Zimmermann (2002) stresses the need to study the likely effects of human disturbances to mangroves. The recommendations made by McHugh (2004), McGuinnes (2003), NTG (2005) and the Darwin Harbour Regional Plan of Management (2003) also explicitly explain the need of an integrated approach for mangrove monitoring.

Most of the catchment, about 80%, is undeveloped and comprises savannah woodlands and forests. They are not in pristine condition due to high fire frequency and access tracks (Skinner et al. 2009). Extensive growth of invasive weeds (gamba and mission grass) during the wet season increases the fire frequency and intensity during the dry season. Further, freshwater lagoons, grassy swamps, paperbark woodlands, floodplains and rainforest cover approximately 6% of the catchment (Skinner et al. 2009). Land clearing and urbanization alter overland flow paths of runoff, reduce the volume of water that infiltrates to groundwater, and the time runoff takes to enter the rivers and creeks. There are about 1150 hectares of nationally significant, mostly dry rainforest in the Harbor catchment. They appear as small patches around the margin of the tidal flats, and most patches are less than 10 hectares in extent (Northern Territory Government 2010). However, there are some large areas of rainforests or vine-thicket habitat at Blaydin Point, Wickham Point, Flagstaff Hill and Kings Table. Fortunately, these forest patches are mostly surrounded and protected by mangroves. The influences from the development pressure are minimal, and forest patches are in pristine condition (Northern Territory Government 2010).

The Northern Territory government initiated numerous water quality studies in Darwin Harbor (Skinner et al. 2009; Smith and Haese 2009). They reported the contribution from urban and rural runoff and point sources. It was shown that land use influences the water quality and flow volume that enter the Darwin Harbor, and consequently changes the water quality of the...
Darwin Harbor. The Harbor itself is a home for a diverse range of marine species: salt water crocodiles, dugongs, marine turtles, and a variety of fish. However, the marine invertebrate fauna of the Harbor region is poorly understood and is still being described. Hence, there is a potential for severe impacts on coastal water quality and overall ecological health of the Harbor due to the increasing population and land developments unless the water quality of rivers and streams entering the Harbor is not well managed.

The ecological endpoints were selected subsequent to this information and expert opinion about the study area. Further, the characteristics that need to be protected for these endpoints were identified.

**Risk analysis**

Risk analysis is the second phase of the RRM. Here, two primary components of the risk: exposure and effects, and their relationship between each other, and ecosystem characteristics were analysed (Figure 2). First, the area can be divided into more homogeneous regions: risk regions for further analysis. Risk regions can be derived based on the topography, habitat or any other criteria that helps to form homogeneous regions. For example, Yu et al. (2014) sub-divided their study area into risk regions based on morphological, ecological, environmental and administrative characteristics. O’Brien and Wepener (2012) introduced a combination of management objectives, source information, and habitat data as criteria for forming risk regions in South Africa. Bartolo et al. (2012) identified sub-regions of Northern Tropical Rivers, Australia based on river basins (catchments). Colnar and Landis (2007) and Hayes and Landis (2004) used watershed and bathymetric boundaries for subdivision of the area, while Moraes et al. (2002) considered the watersheds and landuse of the area. Catchment area limits, boundaries of
environmentally protected areas, territory boundaries, habitat and source types, the flow of tributaries into Mountain river/contours, incremental gradient of human activities of the lower reaches of the catchment are few other criteria used by different studies (Moraes et al. 2002; Obery and Landis 2002; Walker et al. 2001; Wiegers et al. 1998).

Most of Darwin Harbor’s catchment is undeveloped and mainly comprises mangroves, savanna woodlands, urban and rural land uses. We divided the area into different regions considering the boundaries of catchments (drainage boundaries), homogeneity, and data availability for further modelling. Some small catchments were merged with neighbouring catchments that have similar topographical characteristics and land use forming homogeneous sub-regions (Figure 1).

The relationships and the probabilities of interaction between risk components are described by numerical weighting factors called filters (Colnar and Landis 2007; Yu et al. 2014). We identified two filters: a conceptual model pathway from source to habitat as an exposure filter, and a conceptual model pathway from habitat to endpoint as an effect filter. As described by Colnar and Landis (2007) and Wiegers et al. (1998), exposure filters were developed considering two major issues: (a) Will the source release the stressor; (b) Will the stressor then occur and persist in the habitat. The effect filters were developed considering whether the assessment endpoint occur in and utilize the habitat, and whether results from interaction with the stressor are positive (undesirable) or negative (beneficial). If the pathway is completed, we assigned a value of “one” to the corresponding filter, otherwise the value is “zero”. We did not apply weights for exposure and effect filters in this study.
The threats and habitats were ranked based on a two-point scale within the range of 0 - 6, and 0, 2, 4, and 6 represented no, low, moderate and high respectively (Bartolo et al. 2012; Yu et al. 2014). The percentage cover of each threat and habitat within sub-regions were considered for ranking. Then, they were classified according to the Jenk’s optimization method (Jenks and Caspall 1971) in ArcGIS software. This method minimizes squared deviations of class means or considers a goodness of variance fit. The optimization is achieved when the quantity goodness of variance fit is maximized. Hence, the classification is based on the natural grouping that is inherited in the data. For example, when there is a greater possibility of occurrence of one specific threat in one risk region compared to other risk regions, the rank assigned was as six. The rank was equal to zero, when it is very unlikely to occur.

The point source discharge data were sub-divided into the following four different stressors: nutrients (nitrogen and phosphorus); metals (aluminium, arsenic, cadmium, chromium, copper, nickel, lead and zinc); Total Suspended Solids (TSS); and Volatile Suspended Solids (VSS). They were ranked based on the percentage of the number of kilograms per risk region (with respect to the areal extent of the corresponding sub-region).

Relative risk calculation

The quantitative analysis of risks of each region depends on the interaction of all components such as stressors, habitats, exposures and effects. Hence, the magnitudes of the total threats in the risk region, the sum of the potential threat exposure in the region, and the total risk to the ecological assessment endpoints were calculated as explained by Landis and Wiegers (1997), Moraes et al. (2002) and Bartolo et al. (2012). The following formulas were used for the calculation. For example, to calculate the sum of stressors in each risk region, Eqn. (1) was used.
When the stressor has potential to impact habitat, the exposure filter received a value of “one”, and the sum of potential stressor exposure in the region was calculated as Eqn. (2).

$\text{Sum of potential stressors exposure in risk region} = \sum (\text{Stressor} \times \text{habitat})$  \hspace{1cm} \text{(2)}

The total risk to the ecological assessment endpoints in each risk region was calculated as Eqn. (3);

$\text{The total risk to the ecological assessment endpoints in each risk region} =$ \hspace{1cm} \sum (\text{Total risk to ecological assessment endpoint})  \hspace{1cm} \text{(3)}$

**Risk characterisation**

This is the final phase of the risk assessment (Figure 2). The results from the relative risk calculation indicate the regional perspective of risks in the Harbor catchment. The total risk in each risk region, risk in each habitat, and the total risk to assessment endpoints were used to derive site specific information.

**Uncertainty and sensitivity analysis**

As risk predictions in the RRM are point estimates that derive from data and subjective expert knowledge, they are uncertain. There are three main uncertainty categories that can propagate through the RRM. Model structure uncertainty is propagated because key elements are not included in the conceptual model due to a lack of knowledge, data availability and over simplification. Assigning an input value to the model is considered as another source of uncertainty. This specifically related to ranking stressors, habitats with a lack of knowledge of interactions between model components, simplification and assumptions. The quality of the data,
their availability and currency can also be categorised as data uncertainties. The subjective judgements of experts contribute some errors.

Three uncertainty levels (ranks) were used (low, moderate and high). For example, when the data are site specific and high quality, the uncertainty level was categorised as low. When there were no site specific data (or no data), and the quality was poor, outdated, and if we made one assumption due to less knowledge about data, was ranked as medium uncertainty. For example, since residential data of this study is outdated, we updated them with Google Earth images, however, all new buildings near residential areas were assumed as houses, and were ranked as medium uncertainty. If there were no site specific data (or no data), and the quality was poor, outdated, and more than one assumption made due to less knowledge about data, they were ranked as high uncertainty. The discrete probability distributions were introduced to each component as explained by Yu et al. (2014), and Hayes and Landis (2004). For example, for the RRM model components with high uncertainty, a probability of 0.6 was assigned. The adjacent ranks received a probability of 0.2 each. For the model components with medium uncertainty, the probability was 0.8 with two adjacent ranks having the probability of 0.1 each. No distributions were assigned to the components with low uncertainty.

The RRM produced point estimates for risks based on ranks and filters from imperfect data. The Monte Carlo simulation was applied to determine the entire range of possible outcomes and likelihood of achieving each of the model components using Crystal Ball® software. Here, we introduced already defined uncertainty levels of each component and ran the simulations for 1000 iterations. We repeated these simulations different times and noted that there were no differences after 1000 iterations.
The sensitivity analysis was also undertaken using the Crystal Ball® software. This analysis explains the influence of uncertainties of sources to the model sensitivity or parameter uncertainty (Colnar and Landis 2007). The model parameters were classified according to the correlation coefficients that were generated through the sensitivity analysis with respect to their contribution to the prediction of uncertainty. Hence, a parameter that has high impact on uncertainty within the model should obtain high correlation (Colnar and Landis 2007).

RESULTS

Problem formulation

We referred to available literature and expert knowledge to identify sources, stressors and their characteristics, exposure opportunities, the ecosystem components potentially at risk, and ecological effects in the Darwin Harbor catchment. The resultant conceptual diagram shows the interaction between urban or rural activities and their effect on coastal environment (Figure 3).

The major sources of threats for estuarine areas are land clearing for urban and rural developments, land clearing for industrial and communication developments, agriculture, point source discharges and climate change. They will directly or indirectly impact on species and habitat destruction, increased flooding, increasing (velocity and volume) soil runoff with nutrients and chemicals, increasing sedimentation and pollution. For example, vegetation serves to slow the flow of water and increase its infiltration into soil and groundwater storages. This enables the water to flow more gradually into watercourses over a longer period of time. However, because of extensive land clearing throughout most catchments and, especially in more urbanized areas, the increased volume and velocity of water can enter watercourses during flood. When it floods, runoff can carry substances such as topsoil, chemicals, rubbish, nutrients, and oil
and grease from roads. This polluted water can be a significant problem for the health of mangroves. This may lead to the degradation of mangroves unless these stressors are not addressed appropriately. Since runoff from the Winnellie industrial area flows into mangroves of the Darwin Harbor, heavy metal and nutrient concentration have been compared with other areas which are not affected by urban runoff (Askwel 2008). Marginally higher concentrations of heavy metals have been observed in the Winnellie mangrove sediments compared to other sites. However, the conditions of mangroves are poorly studied over time compared with such chemical pollutions.

The accumulation of sediment can greatly be increased by upstream disturbances such as vegetation clearing and urbanisation. Although mangroves colonise sedentary environments, excessive sediment deposits can reduce growth or even kill mangroves (McGuinnes 2003). Complete burial of root structure may disturb gas exchange, killing root tissue and trees (McHugh 2004). Since mangroves are susceptible to pollution, pollutants from urban areas and agrochemicals results in short term and long term effects on mangroves (Askwel 2008) because mangrove environments are a trap for rubbish accumulation. A Darwin Harbor mangrove rubbish survey found the three most common types of rubbish are aluminium cans, plastic bottles and plastic bags (Lewis 2002). They were thought to be sourced from storm water drains, tides and direct littering at the sites, and their rate of decomposition is indefinite or quite high (Lewis 2002).

Currently, there is a major liquefied natural and petroleum gas project around Darwin Harbor being run by INPEX. Subsea pipelines which transport liquid hydrocarbons run between the gas field and onshore at the Middle Arm (Metcalfe 2007). For the entire project, the
proposed land clearing extent is about 300 ha including mangroves. Parallel to this gas project, major industrial developments in the Middle Arm are being discussed. According to a report published by INPEX at different stages of the project, there is a high possibility of increasing sedimentation over certain areas of the Darwin Harbor catchment (Senden et al. 2013).

The point source discharges can either be hot water outflows (storm water drainages) or treated sewage discharges. A hot water outflow from storm drainage reduces mangrove leaf area and increases defoliation (McGuinnes 2003). Increased water temperature shows mortality of seeds. Also at low levels, nutrients entering waterways can lead to increasing productivity by promoting the growth of even algae and plants. One of the consequences of urbanization is discharging pre-treated sewage to mangrove swamps as efficient, low cost and natural wastewater treatment (Lewis 2002). Nutrient pollution in the mangroves can have various effects. Basically, it can enhance tree growth and productivity. On the other hand, excessively high nutrient concentration causes excessive algal growth which can hinder oxygen exchange and mangrove seedling (McGuinnes 2003). Since there are waste water treatment plants around Darwin Harbor (Darwin Central Business District, Palmerston South, Buffalo Creek and Ludmilla Creek), increasing sedimentation and accumulation nutrients as well as pollutants to the mangroves can be expected.

Numerous water quality studies of the Darwin Harbor determined the contribution from diffuse sources. The main nutrient load contributor is sewage effluent and the effect is more significant at a local scale, such as a tidal creek level where point source nutrients are discharges rather than at a whole-of-Harbor scale (Skinner et al. 2009).
Climate change predictions indicate that sea level will increase by one metre during the course of a 20 year period. This will highly affect mangroves with species and habitat destruction showing a backward movement of zonation pattern.

We categorized each source into different stressors (Figure 4). For example, the stressors related to the land clearing for urban and rural developments were identified as residential, transportation, utilities and recreational activities. Utilities are defined as electricity generation and transmission, gas treatment, storage and transmission. The source, land clearing for industrial and communication developments, was divided into three different stressors that included manufacturing and industrial, dredging, and services. Dredging reflects the areas that are going to be affected once the ongoing gas project has completed the onshore dredging. Services include the areas that are allocated to the provision of commercial or public services substantially influencing the natural environment. The agriculture runoff from croplands and horticulture lands are increasing levels of nutrients and turbidity in streams and in mangroves. Available topographic data allowed us to categorise the source agriculture into three different areas: cropping, horticulture and aquaculture.

**Habitats and ecological assessment endpoints**

Since unlocking the many possibilities for increasing infrastructure development along the mangrove dominated shoreline of Darwin Harbor, ensuring the maintenance of ecosystem services and a healthy environment is one of the priority goals of the Government (Harrison et al. 2009; Lee 2003). Although many studies have been undertaken in the mangrove forests of Darwin Harbor to understand this valuable ecosystem, some knowledge gaps still exist. The maintenance of mangrove health (sustainable ecosystem) and maintenance of water quality
(aquatic biodiversity) were selected as assessment endpoints for this study. The attention was given to the management goals of the Northern Territory government (The Darwin Harbor Advisory Committee 2003), the ecological relevance to the stakeholders of the region, and vulnerability to potential stressors.

Most of the areas of the Darwin Harbor catchment are vacant Crown land (Harrison et al. 2009). Although there are a number of habitat types present in the catchment, mangroves, streams, rivers and other water bodies are the most available terrestrial and aquatic habitats that highly influence to the health of the Darwin Harbor. Hence, we selected mangroves and water bodies as habitats of the RRM. Change in species structure, change in habitat for flora and fauna, increase in sedimentation, and influx of nutrients were considered as effects of stressors in mangrove habitat. For water bodies, we accounted for change in waterways, change in groundwater level, influx of nutrients, influx of chemicals, and increase in sedimentation.

The exposure to the stressor creates a possibility of a biological degradation on habitats. For example, the land clearing stressor indicates a reduction of mangrove coverage, change in species structure, reduction of habitat for flora and fauna. Point source discharges exposes an influx of nutrients. As explained in Figure 4, exposure and effect filters were identified for mangroves and water features.

Risk analysis

Based on sub-catchment boundaries, we created 22 risk regions from an initial 42 sub-catchements of the Harbor. For example: Howard River risk region includes six sub-catchments; Blackmore River and Elizabeth River risk regions were formed merging seven and eight of the Darwin Harbor’s sub-catchments respectively. Howard River, Elizabeth River
and Blackmore River risk regions are the largest sub-regions including major river systems. According to Skinner et al. (2009), they are classified as rural type land uses. Further, Sadgroves Creek, Hudson Creek and Reichardt Creek risk regions comprise with the largest area of light industrial land use. Hudson Creek is subjected to an industrial expansion of the nearby East Arm Port. Rapid Creek, Buffalo Creek, Ludmilla Creek and the Darwin Central Business District risk regions include extensive urban areas.

**Risk characterisation**

The total relative risk was calculated for the 22 risk regions. Myrmidon Creek, Blackmore River, Blesers Creek and Elizabeth River risk regions showed the highest total relative risk of ecological assets in the risk region. The Creek A, Sandy Creek, West Arm and the Pioneer Creek were the risk regions with the lowest total relative risk to ecological assets. The model did not calculate the total relative risk to the Darwin Central Business District risk region as its mangrove habitat rank is zero. The Blesers Creek catchment is adjoining to the Winnellie industrial area, and therefore, the percentage of metal, TSS, and sedimentation are high compared to other catchments. Myrmidon Creek is closer to Palmerston city, has influence from residential and industrial areas, and contains a sewage plant and diffuse entry point. Blackmore River and Elizabeth River catchments have high impact from agriculture and point sources.

We investigated the total relative risk to each assessment endpoint separately. The highest risks related to the maintaining mangrove health were found in Sadgroves Creek, Reichardt Creek, Blackmore River, Myrmidon Creek, Blesers Creek and Elizabeth River (Figure 6 (A)). Mangroves of Creek A, Sandy Creek, West Arm and Pioneer Creek are in a pristine condition with low risks. Although we did not include influence from point source discharges to the
Ludmilla Creek risk region, it showed moderate total risk to the ecological assets. If the point source discharges were included, the total relative risk of Ludmilla Creek risk region would be high.

The total risk values obtained for the maintenance of water quality correspond to the risk values for the maintenance of mangrove health (Figures 6 (A) and (B)). Although the risk scores for both maintenance of mangrove health and maintenance of water quality of Buffalo Creek catchment are moderate, this will be high in the near future due to the expanding Lyons and Muirhead residential developments. To the same extent, the Palmerston South and Mitchell Creek catchments will experience higher risk scores due to Palmerston’s new urban footprints: Bellamack and Roseberry suburbs.

**Uncertainty and sensitivity analysis**

The simulations of total risk to each ecological endpoint were modelled. The frequency of the variation of total risk values was shown in Figure 7. As shown in Figure 7 (a), the simulated total risk scores of the Pioneer Creek, Micket’s Creek, Creek A, Sandy Creek and the West Arm are characterised by distributions with data spikes. They indicated less uncertainty in source-habitat-endpoint pathways. The Rapid Creek and the Woods Inlet distributions indicated moderate uncertainty of the components (Figure 7 (b)). However, Reichardt Creek, Blesers Creek, Myrmidon Creek, Palmerston South, Elizabeth River and Blackmore River showed the most widely spread distributions (Figures (b)-(e)). This indicated higher uncertainties of model components.

The sensitivity analysis calculated rank correlations for all model components (i.e. risk regions, sources, habitats, and assessment endpoints). The rank correlation indicates whether the
uncertainty of any model component has an effect on the uncertainty of the forecast. Figure 8 shows the rank correlation coefficients of the risk regions having the highest total risk scores. These graphs show the relative magnitude of influence for each variable. Assumptions made for water bodies within the Elizabeth River, Blesers Creek, and Blackmore River risk regions have a dominant effect on the uncertainty of the forecast (Figures 8 (A), (B) and (D)). In two instances (Blackmore River and Elizabeth River), it accounted nearly 80% of the variation in forecast values, and can consider as the most important assumption in the model. Treated sewage/nutrients of the Elizabeth River contributed least to the forecast variance. It means that this assumption has a small effect; it could be ignored or even could be eliminated from the analysis. The influence from the habitat mangroves was relatively higher than other components.

DISCUSSION

Ecological risk assessment is an important tool for supporting and improving environmental decision-making. The RRM was used as such a tool for assessing the impact of potential sources on habitats within the Darwin Harbor catchment in the context of ongoing developments. A conceptual model integrating existing information and expert opinion focused on describing source-habitat-endpoint pathways was developed as an important foundation in the RRM process. This approach to conceptual model development has limitations, and we suggest organising a series of stakeholder meetings to gather information rather than informal meetings for future work. This would facilitate stakeholders to share their own perspectives, come to agreement on what the conceptual model should include, and to avoid subjective opinions.

Accurate and current spatial information is required for aquatic habitats, point source discharges and land clearing. For example, we did not obtain point source data for the Ludmilla
Creek risk region which encompasses an abandoned treated sewage discharge point. The Mitchell Creek risk region does not include the influence from the recently populated Bellamack suburb. The current stressors and effects from the LNG project in the Harbor need to be incorporated, especially those effects due to the increase in sedimentation.

Although the results of the RRM applied here are representative of current knowledge of stressors and effects on mangroves, we would recommend applying the model to individual sub-catchments (42) rather than the merged sub-catchments that resulted in the 22 risk regions. For example, the nutrient and total pollutant loads of the Howard River, Blackmore River and the Elizabeth River are higher than other risk regions due to their larger areal extent (Skinner et al. 2009). However, to minimize such effects in this study, we calculated the percentage of kilograms per each point source values with respect to the areal extent of each risk region.

It is clear that catchments with a high percentage cover of industrial and commercial land use, and residential areas received the highest risk to each ecological endpoint. Mangroves close to development and population centres suffered some clearing and localized damages from contaminants. These catchments received higher ranks for residential, nutrients, metal, and VSS than undeveloped areas. For example, Elizabeth River risk region has the highest total risk to the ecological endpoints, and dredging, horticulture, cropping and aquaculture obtained relatively high ranks. Mangroves and waterbodies also ranked high. The Creek A obtained the lowest total risk to the ecological endpoints. Currently, although there is high impact from sea level rise and sedimentation stressors to this risk region, other stressors have minimal or no impact. Further, mangrove habitat was also ranked high due to impacts from sedimentation and sea level rise. The prediction of climate change effects has a major role in risk to mangroves. Due to the elevation
variation of the catchments, some areas will suffer from climate change effects or sea level rise. Most of the catchments where the total risk of ecological assets is low have less influence from land clearing for industries, diffuse entries and climate change.

This model provides a robust framework for assessing the regional ecological risk and the benefit of Monte Carlo analysis in describing uncertainty in a RRM. The outcome of this study should not be used for decision making; rather it can be used as a framework for future studies. This is a useful approach for integrating all components: multiple assessment endpoints, threats and habitats together, and addressing the knowledge gap. According to the Northern Territory’s long-term development plan, parts of Mitchel Creek, Palmerston South, Elizabeth River and Blackmore River will become residential and light industrial areas to accommodate the increasing population. These catchments already have high or moderate levels of risks. For example, Palmerston South risk region already accounted for high risks for various stressors namely: residential, utilities, sedimentation, sea level rise, waste water/metal, and stormwater drainage/suspended solids. Hence, this is an important issue to be considered when making decisions. The development plan is being proposed for the Middle Arm of the Darwin Harbor (the City of Weddell) especially for the Pioneer Creek catchment. Currently, the Pioneer Creek catchment experiences low total risk of the ecological assets compared to others. For example, it has low impact from stressors: land clearing for residential and transport and communication, sedimentation and point sources discharges and surface runoff, and there is no influence from other sources. The proposed developments will increase the land clearing for residential and commercial activities, and subsequently the total relative risk of the region. To the same extent, Skinner et al. (2009) predicted a significant increase of pollutant load as a result of these
developments. Therefore, this is another important issue to be considered by the decision makers. Instead, the risk regions with moderate total risks, for example, Sandy Creek and Kings Creek have more possibilities for developments. Currently, these risk regions have minimal or no influence from the majority of sources such as agriculture, aquaculture, climate change, and land clearing for residential or commercial developments. However, although the RRM can provide useful information about the ecological risk of corresponding areas, it is difficult to select one risk region over another for locating developments without a proper methodological approach.

The Integrated Water Resources Management (IWRM) approach promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems. This has been introduced by the Global Water Partnership (GWP) (Global Water Partnership 1996). According to IWRM, stakeholder participation, river basin planning, pollution control, and monitoring are few activities that constitute water management. This is a similar approach as to what has been undertaken through the “Darwin Harbour Strategy” by the Northern Territory Government.

The “Darwin Harbour Strategy” is a guide for sustainable development of the Darwin Harbor region, and it supports the integrated management of the Darwin Harbor region’s diverse environmental, social, cultural and economic values and uses. However, the Northern Territory's water resources are considered to be under relatively little pressure due to a comparatively small population base and low intensity of land use in the catchment. This situation is changing due to a predicted increasing population in the near future and therefore the Northern Territory is increasingly becoming subject to higher demands, so integrated assessment approaches are
recommended. Hence, we would also suggest continuing the already introduced “Darwin Harbour Strategy” approach to have coordinated development and management of water, land and related resources in the region.

In summary, increasing population and consequent land development has a potential for more severe impact on water quality and ecological health of the Darwin Harbor catchment. For example, the potential increase of pollutant load and nutrient load from the medium and long-term plans for the Harbor catchment developments has already been predicted. Land clearing, residential and industrial activities will increase. Therefore, we demonstrated the successful application of the RRM to assess these risks. The model is repeatable and can use to predict the ecological risk in the near future with various scenarios.

**Uncertainty and sensitivity analysis**

Although the Darwin Harbour catchment is a rapidly developing area, Blackmore River, Howard River and Elizabeth River catchments are classified as rural land uses compared with catchments closer to the Darwin Central Business District which are classified as urban areas. These rural areas are poor in data availability and data quality. Available topographic data are outdated; more than 10 years old. For example, through the sensitivity analysis, the waterbodies data contributed to the majority of uncertainty for the Elizabeth River, Blackmore River, and Bleezers Creek catchments as there is less spatial data available for waterbodies in these catchments (Figure 8). The error contribution from mangroves to the risk analysis in Blackmore River, Elizabeth River, Myrmidon Creek and Bleezers Creek regions are also higher than other regions. The mangrove coverage spatial data set is almost 20 years old, and it does not include already cleared and newly regenerated areas exhibiting higher data uncertainty. For instance, the
mangrove clearing in the Middle Arm due to the activities of the natural gas project is not included in the analysis. Therefore, the main limitation related to this application is data input. The outdated or lack of data impacts the analysis. Although we updated newly formed residential areas using Google Earth, there may be some errors associated with this interpretation due to difficulties in determining industrial and residential land use from the satellite imagery without field verification (that is, both cover types appear similar in the imagery).

The introduction of subjective expert opinion may add some gross errors to the model. The ranks, exposure and effect filters are subjective. This subjectivity can change the model outputs. A further issue related to the conceptual model is that the model can over-simplify the real world situation. The assigning of ranks in the uncertainty analysis is subjective. This is also based on expert opinion and existing information. Hence, we would recommend organising a series of stakeholder meetings and gathering information from various users, and collecting current information before implementing the RRM. If uncertainties are minimised, the RRM can be used by decision-makers and land managers to prepare action plans to reduce threats from urban development to the coastal environment and mangroves.

CONCLUSIONS AND RECOMMENDATIONS

There are many ongoing and proposed industrial, commercial and residential development projects in the Darwin Harbor catchment, and subsequently the natural resources of Darwin Harbor region are experiencing an increasing development pressure. As it is necessary to ensure the balance between these developments and conservation, appropriate tools that combine knowledge from different sources into a consistent environmental management framework are needed. One of the key requirements for environmental monitoring programs in Darwin Harbor
is an integrated approach for ecological risk assessment that enables stakeholders to make practical and sound management decisions. Therefore, in this study, we introduced the application of a RRM to assess the ecological risk of the Darwin Harbor, and this application is a significant contribution to the current knowledge in this context.

The application of the RRM involves three major phases: problem formation; risk analysis; and risk characterization. We investigated existing knowledge and consulted expert opinion in the problem formation phase. Then, a conceptual model was created combining all information. Spatial data from topographic databases and statistics relating to various Darwin Harbor monitoring projects were collected.

In the second phase of the analysis, we identified the ecological endpoints and corresponding model components including sources, stressors and habitats. The management goals of Darwin Harbor were considered in determining the ecological assessment endpoints which were the maintenance of mangrove health and the maintenance of water quality. The large Darwin Harbor catchment boundary and boundaries of sub-catchments were adapted from the Australian Collaborative Land Use Mapping program (V5). However, homogeneous small catchments were merged and formed 22 risk regions for further analysis. We created a RRM to rank and sum each source of stressors, and habitat in each risk region. Once model components were ranked according to the percentage coverage of sub-regions (with respect to individual areal extent), the pathway of sources-habitats-endpoints was created.

Risk characterisation is the last phase of the modelling process. The uncertainty of each model component was investigated and classified into low, medium and high, and the discrete probability distribution was introduced. The Monte Carle simulation was used to obtain all
possible values of risk scores. We analysed the total relative risk of the ecological assets in risk regions. They were classified into three classes according to the Jenk’s optimization.

The sub regions: Myrmidon Creek, Blackmore River, Blesers Creek and Elizabeth River showed the highest total relative risk to ecological assets in the risk regions. Creek A, Sandy Creek, West Arm and Pioneer Creek showed the lowest total relative risk of ecological assets. The study did not calculate the total relative risk for the Darwin Central Business District region. These results indicated that risk regions with a high percentage cover of industrial, commercial, residential areas, diffuse entry points, and climate change effects contributed to the highest risk to each ecological endpoint.

The relative risk model is a robust application that is suitable for a large geographic area where multiple stressors are of concern. Data uncertainty is the major limitation associated with the model. For example, one of the selected habitats to be analysed is mangroves and spatial data on mangrove coverage is almost 20 years old. It does not include either recently cleared or regenerated mangrove areas. We would not recommend using these results for decision making due to the various uncertainties, however, this can be used as a framework for future studies. We further would recommend organising a stakeholder meeting at the first phase of the model for data collection. This will reduce the effect of subjective opinions. We would also suggest continuing the already introduced “Darwin Harbour Strategy” approach to have coordinated development and management of water, land and related resources in the region.
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Figure 1: The Darwin Harbor catchment and its mangrove distribution.
Figure 2: The workflow diagram for conducting an ecological risk assessment using the Relative Risk Model following the guidelines published by the U.S. Environmental Protection Agency.
Figure 3: The conceptual diagram showing estuarine activities and their effect on mangroves, water bodies and then to the Darwin Harbour.
Figure 4: The conceptual model for the relative risk modelling in the Darwin Harbor. They were prepared for all risk regions. Exposure and effect filters were modified with respect to each risk region.
Figure 5: The total relative risk to ecological assets in risk regions of the Darwin Harbor. They were classified as low, medium or high based on the Junk’s optimization.
Figure 6: Total risk scores for the ecological endpoints; (A) Maintenance of mangrove health; (B) Maintenance of water quality.
Figure 7: The frequency of all possible outcomes of total risk of ecological assets in the risk regions.
Figure 8: The rank correlations for sub-regions having the highest total risk scores: (A) Blackmore River; (B) Elizabeth River; (C) Myrmidon Creek; (D) Blesers River.