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Development of a Methodology for Estimation of Ballast Water Imported to Australian Ports

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ABSTRACT

The importance of identifying the location and magnitude of risks imposed from ship-mediated bioinvasion in Australia is significant after the assessment of previous events that have impacted the Australian ecosystem and economy. This paper provides an overview of the developed methodology adopted for the estimation of ballast water imported to Australian ports. The resultant amount of ballast water discharged for a total of 31ports in a period of five years was estimated and results were presented. A high level of risk was identified at the north-west of Australia, where 60 percent of the total ballast water imported was discharged for the year 2013. A significantly large amount of ballast water was also discovered in the regions of Newcastle and Hay Point. It was discovered that bulk carriers account for 94 percent of mediated ballast water. Proportion factors for predictions have been established based on the relation between the mass of freight exported with the amount of ballast water discharged. The study recommends a sensitivity analysis of proportion factors based on varying selected deadweight for individual ship type and size categories. To mitigate risks from ship-mediated bioinvasion, the origin of the ballast water imported should be investigated as well as the type of foreign marine life introduced. The development of a methodology in the classification of ship sizes for general cargo ships, LPG/LNG, livestock and vehicle carriers was suggested to improve the accuracy of the estimation.

KEYWORDS: Bioinvasion, vessel traffic, automatic identification system, artificial neuron network, deadweight tonnage, gross tonnage, proportion factor.

1 INTRODUCTION

A major contributor to the introduction of foreign aquatic species in a coastal ecosystem is that which is imported through ballast water in vessels. *Glo Ballast*, a Global Ballast Water Management program hosted by the International Maritime Organization (IMO), recognises that the introduction of invasive marine species is the primary source of threat to the ocean and to biodiversity globally[1]. Approximately 80 percent of the world's commodities are moved through shipping and 3 to 5 billion tonnes of ballast water is translocated internationally, annually. This indicates the magnitude of the potential spread of foreign marine species, which may affect the Australian marine environment. Specifically in Australia, approximately 200 species have come to inhabit the local environment via ballast water or hull fouling from foreign vessels. Numerous events have caused a major impact, which led to the introduction of foreign species such as the following[2]:

- The toxic dinoflagellate (*Gymnodiniumcatenatum*), which affected southern Tasmanian shellfisheries, caused the industry to go out of business for a period of six months.
- Introduction of the Northern Pacific Seastar (*Asteriasamurensis*) has resulted in a drastic yield reduction in the Tasmanian scallop industry.
- The Giant Tube Worm (*Sabellaspallanzanii*), a filter feeding species established in southern Australia, which has removed several species organisms from the base of the food chain, thus having the capability to disrupt the natural ecosystem.
- Mussels that were introduced in Cairns and Darwin caused a financial loss as a result of attempting to eradicate them before further damage occurs.

The incidences above have been selected to exemplify the severity of the infestation and the potential impacts on the Australian ecosystem and economy. This signifies the importance of ballast waters management in Australian ports as the effects are detrimental to the marine environment and the damaged caused will be irreversible.

Currently, there are several treatment methods for ballast water that are being practised in the industry. These include: the high velocity sonic disintegrator (HVSD), ultra violet irradiation, filtration, addition of chlorine dioxide or a combination of these systems[3]. However, the risk of introducing foreign marine species remains as only limited developed treatment systems are produced in the market and the efficiency of such systems is uncertain. In order to recognise the magnitude of risk imposed in each port in Australia, it is essential to formulate an approach to

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quantifying such risks. This involves methods such as identifying the origin of the ballast water, monitoring the pattern and approximating the amount of ballast water discharged at individual ports.

A previous investigation carried out by Enshaei & Mesbahi[4] in relation to developing a methodology for estimation of ballast water provides an insight into the approach for this research. Their investigation was performed on ports in the United Kingdom. The ideology of the estimation was to correlate the ship's cargo operations and their ballast water with their sizes. A software package known as *BalEsti Mate,* developed at Newcastle University, was used to estimate ballast water capacities based on the vessel type and size. Coefficients were developed and the estimation of ballast water capacity for each vessel with respect to their size was made possible. Finally, a relationship between both parameters was determined.

Several models were analysed prior to the development of the methodology for the research. These models include the Great Lakes model, European model and Brisbane model. Being one of the very first models produced, the Great Lakes model was identified as an imprecise method of estimating discharged ballast as the calculations involved are rather simple. The estimation was based on taking average or typical loads on incoming Ballast on Board (BOB) vessels which entered St. Lawrence Seaway and the Great Lakes. Consequently, the model was claimed to beunreliable as it does not take cargo operations and ship's size into consideration[5].

The European model, created in 1996 by a group of European experts during their study on ballast water, was another model that was analysed[6]. This model has an advantage over the others as it takes the influence of foreign trade into account and introduces a new perspective in regards to the percentage of the ship's deadweight. On the other hand, the model does not take transit cargo and the type of cargo into consideration. Hence, as advised by the author, the model should be used for rough estimation only.

The Brisbane model, which was developed by Dunstan and Bax[7]in 1994, was also analysed. This model was created based on a simple calculation whereby the ballast water discharged can be estimated by multiplying the deadweight sum of all ships by 38 percent. However, the relation between the vessel's ballast capacity and its deadweight is not always 38 percent. Furthermore, cargo operations were not considered within the model, thus making the model unreliable.

A study conducted by Suban et al.[8]in Port of Gdynia was examined. The model used in their investigation included the following considerations and parameters:

- The ship is not always loaded to the full deadweight capacity.
- Deduction of weight from stores, fuel, fresh water and other weights, which represent approximately 5 to 10 percent of the ship's deadweight.
- Type and weight of cargo carried.

The authors suggested that the model was unable to yield satisfactory results due to insufficient data. However, it was concluded that the model would have been a more accurate model as compared to previous models as it was based on cargo operations, type of cargo and on the ratio between discharged cargo quantity and the vessel's deadweight.

In February 2009, the Danish Maritime Agency initiated a project that was aimed to estimate the amount of ballast water discharged in Danish waters[9]. The methodology adopted in the investigation was based on a model developed by Stephan Gollasch[6], a researcher from Germany. The Danish Bureau of Statistics or *Danmarks Statistik* provided key data such as ship types, number of calls, deadweight and ballast water capacity. Through the collected data, the ship type was characterised with respect to ballast water, multiplied by the total number of calls and the proportion of ballast water discharged from international traffic was identified. Results showed an estimated amount of 1,423 million tons of ballast water was discharged in Danish waters, with 69 percent of ballast water originating from foreign countries. It was also discovered that 97 percent of ballast water was discharged by tankers from international trade.

Dr Gollasch[6] has outlined a few discrepancies that were discovered within the model. The model did not take general cargo ships into consideration. Although these ships only discharge minimal amounts of ballast water, nevertheless the number of calls and their frequency is high. Furthermore, the model did not include discharged ballast water during ship-to-ship operations. Subsequently, the Danish Maritime Agency decided to carry out another method of estimation. The proposed method was to relate the amount of ballast water discharged to the amount of loaded goods. Studies indicated that ballast water represents 30 to 40 percent of a ship's deadweight[1].Therefore, it was assumed that any loading operation would lead to a ballast water discharge of 30 percent of the cargo loaded. With the cargo data that were provided by *Danmarks Statistik*, the amount of loaded goods was known, thus the amount of ballast water discharged in Danish ports can be estimated. The total amount of ballast water discharged was found to be 17 percent lower than the amount predicted with the Gollasch model. According to Kern and Stuer-Lauridsen[9], the Gollasch model uses a higher average deadweight than the actual average deadweight of ships visiting Denmark, hence causing the overestimation. The author concluded that more detailed data on type of vessel, deadweight and loaded amounts would improve the quality and accuracy of the estimates.

Through the analysis of previous studies, it is evident that the amount of parameters considered in the estimation does significantly affect the accuracy of the estimation. Moreover, the quantity and quality of resources obtained from ports will govern the amount of parameters that could be taken into consideration in the development of the methodology. An in-depth description of the methodology adopted for this research is provided in Section 2.

2 METHODOLOGY

The investigation undertaken follows the methodology as illustrated in the process flow diagram, Figure 1. A software package created with Microsoft Excel was utilised to assist in the estimation of amount of ballast water discharged at all ports. Principles and design basis in the creation of the software is further discussed in this section.

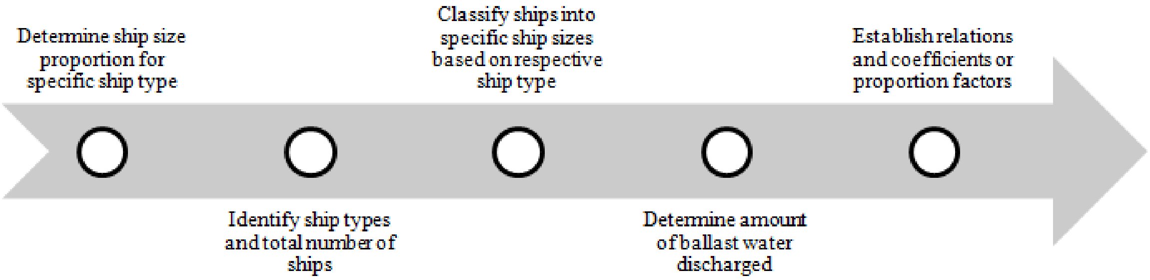

Figure 1: Process flow of investigation

2.1 Data Collection

Prior to conducting the investigation, data from individual ports has to first be collected. Data for a period of five financial years, from June 2009 to July 2014, were collected. In Australia, the financial year starts on the 1 July and ends on 30 June. It is important to note that ballast water is discharged only when cargo is loaded onto the vessel. Therefore, data of interest for the investigation focus on vessels that export freight. Any information regarding the mass and type of freight to be exported was collected, as well as the number, type and size of ships exporting freight. Typically, trade statistics from individual ports were first collected and then analysed. However, it was discovered that several ports do not release detailed statistical data due to port security restrictions, therefore an alternative method of determining ship sizes for specific ship types was employed.

Ports Australia[10] is an organisation that has preserved an archive of trade statistics from the years 1997 to 2013.The organisation provides statistical data that include the mass of individual commodities exported from all ports, hence the identification of ship type was made possible. However, information on the number and sizes of ships exporting freight were not stated. To obtain this information an alternate source, namely *Marine Traffic,*[11] was utilised. *Marine Traffic* is essentially a website, which tracks vessel positions based on automatic identification system (AIS) data. The website provides information on shipping movements, including the identification of vessels in port, recent arrivals and departures and expected arrivals. It was from this source that the ship type and size or deadweight was collected for each port. Additionally, shipping movements from individual ports were also collected to populate the quantity of data. Typically, individual ports provide a month's worth of shipping movement data. Conversely, ports with a lower level of security restrictions, such as Port Hedland and Bunbury, offer an archive of shipping data spanning several years.

A total of 46 ports were identified, however only 31 were included in the estimation. The 15 ports that were excluded were minor ports that were considered less significant as they export less than 1 million metric tonnes (MMT) per financial year. Furthermore, only minimal amount of data were found for these ports, hence the results yielded would have been inaccurate. A number of ship types were not included in the estimation as the impacts of these ships were discovered to be less significant than the rest. Ship types that were included were: tankers, containers, general cargo ships, LNG/LPG, vehicle, livestock and bulk carriers. Excluded from the estimation were ship types such as: dredgers, barges, yachts, tugs, passenger, patrol, pilot, naval and research vessels.

2.2 Data Processing

Statistical data that were collected commonly provided information on ship types, number of vessel calls, and mass of individual commodity imported or exported. However, ports with a lower level of security restrictions, as mentioned previously, provide extensive information such as individual ship sizes. In this investigation, spreadsheets consisting of data cells ranging between 100and 100,000 cells per financial year were analysed and processed. The amount of data would reflect the level of detail provided. Therefore, the presentation of data varies from port to port, requiring different techniques for analysis. This subsection provides a general overview of the principles guiding the data analysis and processing methods.

2.2.1 Determination of Ship Size Proportion

The first stage of data processing was to determine the ship size proportion for all ship types. Based on the shipping movement data that were collected, individual vessels were categorised into ship sizes based on their deadweight. Table displays categories for ship sizes based on the deadweight range for tankers, bulk carriers and container ships. As investigating the amount of ballast water discharged for each individual ship would be time consuming, a selected deadweight was chosen for each ship size category and used for the estimation. Through the vessel counts for each size category for tankers, bulk carriers and container ships, ratios or proportions were obtained and used for the analysis. General cargo ships, vehicles, LNG and livestock carriers were analysed differently as most of these ship types were discovered to have a small deadweight range. Instead of classifying vessels into different size categories, an average deadweight for each ship type at individual ports were taken and used in the investigation.

Table 1.Selected deadweight (DWT) for specific ship types and sizes

Ship Type	Ship Size	DWT Range (tonnes)	Selected DWT (tonnes)
Tanker	Handy	< 50,000	40,000
	Panamax	50,000–80,000	65,000
	Aframax	80,000–120,000	100,000
	Suezmax	120,000–200,000	160,000
Bulk Carrier	Handy	< 40,000	30,000
	Handymax	40,000–60,000	50,000
	Panamax	60,000–80,000	70,000
	Post-Panamax	80,000–110,000	95,000
	Capesize	110,000–200,000	155,000
	VLCC	> 200,000	210,000
Container Ship	< 2,499 TEU	< 34,026	27,532
	2,500–3,999 TEU	34,026–53,506	43,766
	4,000–4,999 TEU	53,506–66,494	60,000
	> 5,000 TEU	> 66,494	72,987

2.2.2 Identification of Ship Types and Number of Ships Estimation

Identification of the commodity type exported by any particular ship provides information which assists in the classification of ships into their specific ship types. Furthermore, shipping movement data from ports usually provide the name, International Maritime Organization (IMO) number and ship type for each individual ship. Where the ship type could not be identified, the name or IMO number was searched for on the *Marine Traffic*[11]database and the ship type was determined.

It was discovered that information on the number of ships that export freight throughout the year was unavailable for most ports. Therefore, Equation 1 was established to estimate the total deadweight (DWT) for the ships that export freight. The relation was established based on the study conducted by Suban[8]whose research suggested that weights from stores, fuel, fresh water and other weights represent approximately 5 to 10 percent of a ship's deadweight. Through this relation, deadweight can then be said to be approximately 5 percent more than the mass of freight exported, thus the formulation of relation displayed in Equation 1.

$$DWT = Mass\ tonnage\ exported\ \times 1.05 \qquad \text{Eq.1}$$

Trade statistics collected from *Ports Australia* categorise the mass export of freight based on each commodity. These statistical data were paired with the relation to the ship types as shown in Table 2. Thus, with the total deadweight determined for the yearly ship calls, and for each ship type, the total number of ships for individual ship type was estimated.

Table 2. Ship type used to export the respective commodities along with respective coefficients for the conversion between deadweight and gross tonnage

Ship Type	Commodity exported	DWT - GT
Tanker	Oil and petroleum	0.5354
Bulk Carrier	Bulk cargo	0.5285
General Cargo	General cargo	0.5285
Container Ship	Containerised trade	0.8817
LNG Carrier	Gas	1.13702
Vehicle Carrier	Motor vehicles	2.7214
Livestock Carrier	Livestock	0.5285

2.2.3 Classification of Ships into Specific Ship Sizes Based on Ship Type

The determined ship size proportion for each ship type as mentioned previously in Section 2.2.1 was utilised. Here, the number of ships for each ship size category was approximated through the determined total deadweight with Equation 1, divided by the product between ship size proportion and the respective selected deadweight. The relation can be simplified with Equation 2.

$$No. of\ ships = \frac{Total\ DWT\ for\ ships\ exporting}{Ship\ size\ proportion \times Selected\ DWT} \quad \text{Eq.2}$$

2.2.4 Determination of the Amount of Ballast Water Discharged

After the breakdown of the number of ships based on ship types and sizes, the amount of ballast water discharged was estimated. The use of a software package, namely *BalEsti Mate* that was developed at Newcastle University, was utilised in the assistance of ballast water capacity estimation, based on the ship type and size[4]. The software uses artificial neural networks (ANNs) to obtain information, where information was previously input by users based on historical data.

The software uses gross tonnage as an input source for ship size and outputs the respective estimated ballast water capacity. As data collected for ship size were in deadweight, a conversion to gross tonnage had to be implemented. According to a study conducted by Takahashi[12], the gross tonnage of a vessel can be estimated by multiplying coefficients into the vessel's deadweight. These coefficients were established based on historical data and were found to be dissimilar based on the varying ship type. The coefficients used are displayed in Table 2.

2.3 Data Analysis

2.3.1 Establishment of Relations and Coefficients or Proportion Factor

To simplify the process of estimating the amount of ballast water discharged for future predictions, a proportion factor between the ballast water discharged and mass of freight exported was determined for individual ship types for five financial years. Trends along the years were then investigated and the subsequent results are displayed and discussed in Section 3.

2.4 Assumptions, Justifications and Limitations

Equations 1 and 2, as described in Section 2.2.2 and 2.2.3 respectively, were formulated based on the assumption that vessels load cargo to their maximum capacity for exporting, which in most cases is true as justified in detailed trade statistics provided by Port Hedland. Similarly, the assumption also applies to the software *BalEsti Mate* as this software estimates the maximum amount of ballast water capable of being discharged by vessels. Furthermore, livestock carriers were assumed to discharge the same amount as general cargo ships. This assumption was made due to the unavailability of estimation for livestock carriers in *BalEsti Mate*.

The lack of abundance of detailed data was found to be a limitation in the investigation. As mentioned previously, most ports do not supply adequate information for the determination of ship sizes. Hence, a ship size proportion, as discussed in Section 2.2.1, had to be utilised in the investigation. The accuracy of the proportions is governed by the quantity of resources that could be obtained from ports or external sources.

3 RESULTS

3.1 Identification of Location and Magnitude of Risk

In order to mitigate risks of ship-mediated bioinvasion, it is important to first identify the location and magnitude of ballast water discharged. This is illustrated in

Figure 2 for the financial year of 2013.

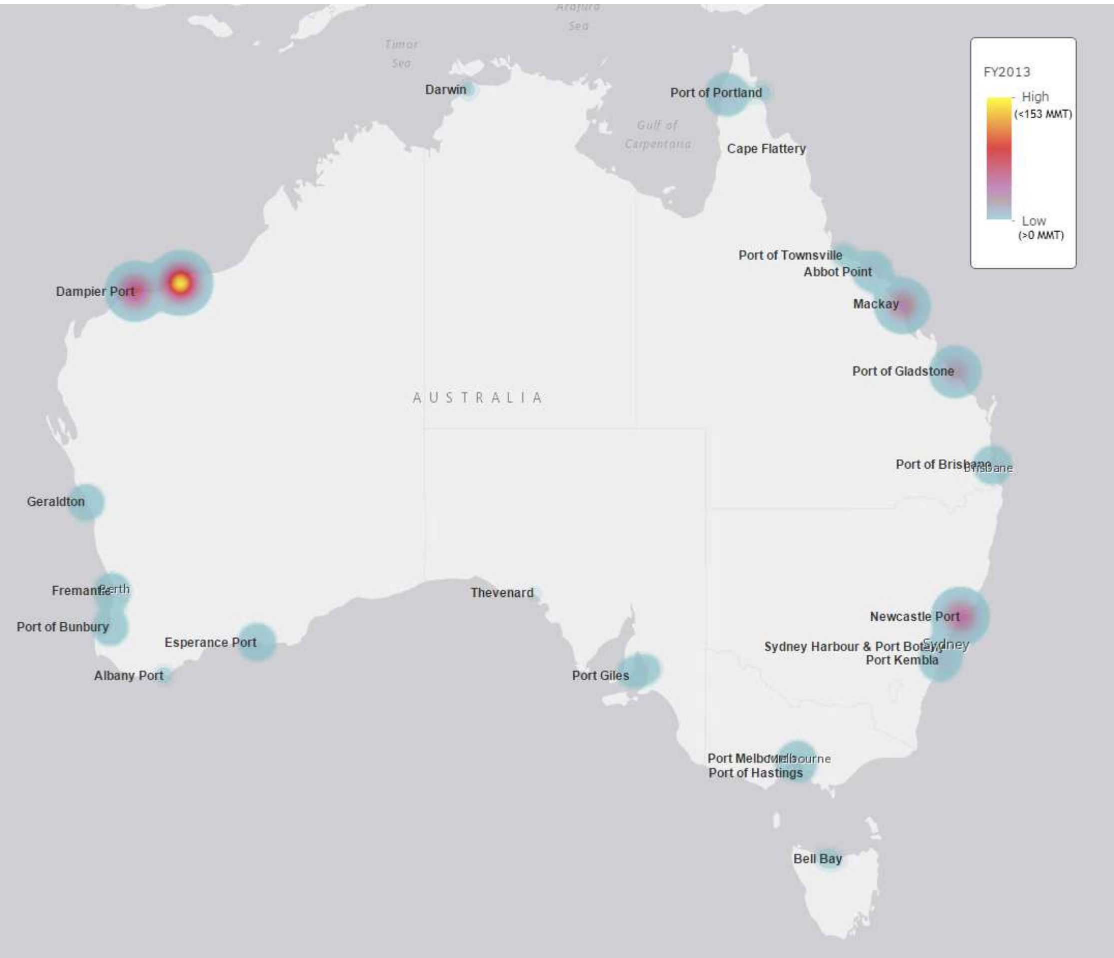

Figure 2: Location and magnitude of ship-mediated bioinvasion risk in Australia

It can be observed that a high quantity of ballast water is discharged in the north-west of Australia, particularly in the areas of Port Hedland and Dampier. A significantly large amount of ballast water is also found in Newcastle and Hay Point (Mackay). The top 10 ports discharging the most amount of ballast water was identified and a Pareto chart was plotted as shown in Figure 3. The four previously mentioned ports primarily dominate the other ports in the amount of ballast water discharged. As illustrated in Figure 3, these ports make up approximately 85 percent of the total amount of ballast water discharged, amongst the top 10 ports identified.

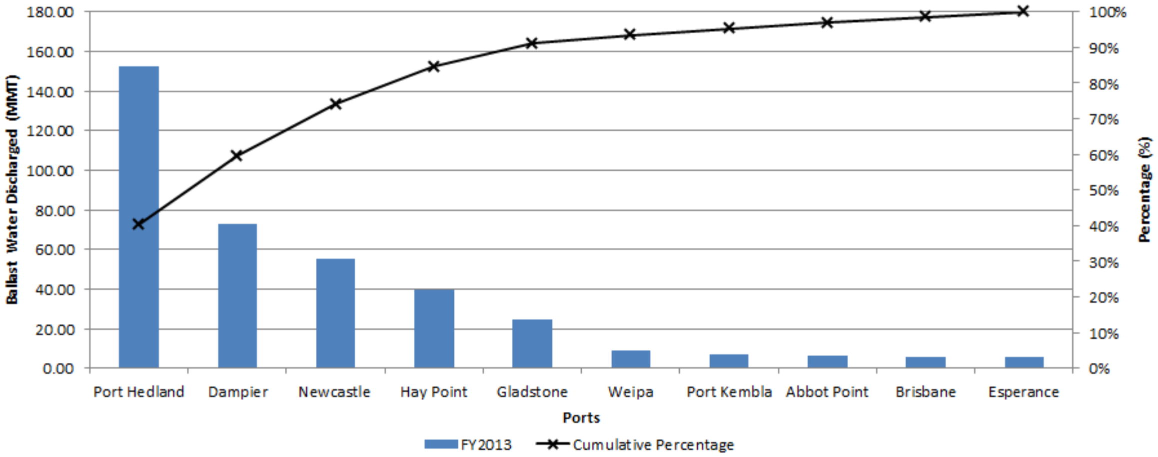

Figure 3: Identification of top 10 ports by amount of ballast water discharged

The amount of ballast water discharged by individual ship types was analysed for the financial year 2013 and the results produced are displayed in Figure 4. Through the chart, it is evident that approximately 93.88 percent of ballast water imported into Australia is transported by bulk carriers. Evaluation of a similar study conducted by Cope et al. confirms the dominance of bulk carriers in Australian shipping traffic and suggests that this is the ship type with the greatest increase in frequency of visits[13].Tankers and container ships were respectively estimated to import 2.62 and 2.29 percent of ballast water. Other ship types were discovered to discharge ballast water less significantly.

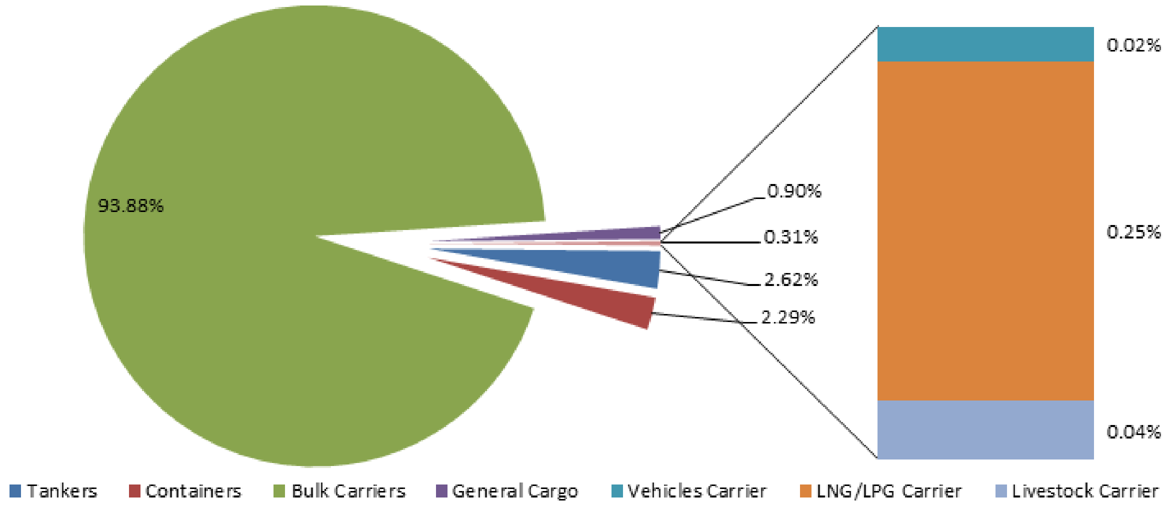

Figure 4: Ballast water imported by specific ship types

3.2 Proportion Factors for Predictions

Figure 5 and Figure 6 display the weight of freight and the amount of ballast water discharged in each state for the respective financial years. General intuition would suggest that both graphs would indicate similar trends, which can be observed in most states. However, particularly in South Australia and Tasmania, trends have been discovered to be dissimilar. Factors affecting these trends are further discussed in Section 4.

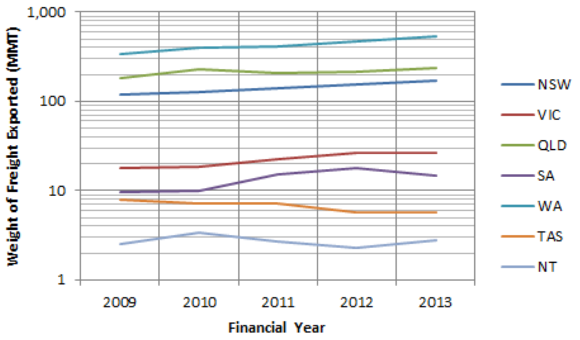

Figure 5: Weight of freight exported from Australian states for five years

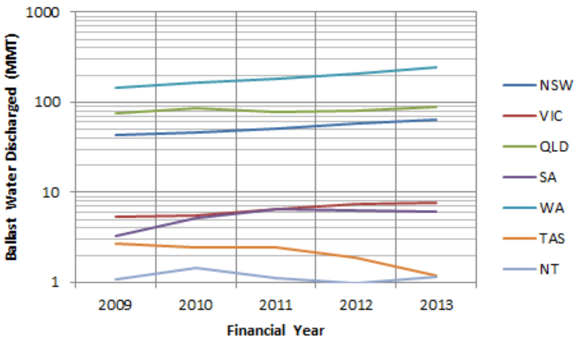

Figure 6: Amount of ballast water discharged in Australian states for five years

With the attained results, the development of proportion factors for the predictions was made possible. These proportion factors are used in the prediction of the amount of ballast water discharged, based on the mass of freight exported. The proportion factor was developed with Equation 3, where the ballast water discharged is divided by the mass of the specific freight exported, for any given ship type.

$$\mathit{Proportion\ factor} = \frac{\mathit{Ballast\ water\ discharged}}{\mathit{Mass\ of\ freight\ exported}} \qquad \text{Eq.3}$$

Table 3 indicates the range and average of proportion factors that were determined based on individual ship types. Bulk carriers, tankers and container ships showed a low range of proportion factors, thus the averaged proportion factor is applicable for a rough prediction of ballast water discharged. However, a large range of proportion factors was discovered for ship types including general cargo ships, livestock, LNG/LPG and vehicle carriers, due to the varying results produced from individual ports. Therefore, inaccurate predictions will be produced if the averaged proportion factor was utilised. Further detailed description regarding the proportion factors are found in Section 4.

Table 3. Range and average of proportion factors for specific ship types

Ship Type	Proportion Factor	
	Range	Average
LNG Carrier	0.55–0.97	0.732
Livestock Carrier	0.27–0.88	0.440
Bulk Carrier	0.30–0.45	0.376
Tanker	0.31–0.34	0.326
Container Ship	0.29–0.33	0.305
General Cargo	0.14–0.67	0.300
Vehicle Carrier	0.17–0.45	0.250

4 DISCUSSION

The key result which significantly affects future predictions in the estimation of ballast water discharged is the proportion factor as described in Section 3.2. Factors yielding variations include ship types and their respective sizes. This section examines the varying factors and resultant proportion factors occurring with regard to container ships, bulk carriers and general cargo ships. The proportion factors displayed are averaged over the five financial years investigated. The section also provides a discussion of comparison between methodologies and the percentage error yielded.

4.1 Container Ships

The top 10 ports exporting containerised trades were identified and the resultant proportion factors along with the varying ship size proportions in each port are shown in

Figure 7. The graph indicates that smaller ship sizes would yield a larger proportion factor than larger ship sizes. Smaller vessels with a high frequency of call would discharge a larger amount of ballast water than larger vessels, when the total mass of freight exported is equivalent. This is evident when comparing the Port of Melbourne with Burnie, where a proportion factor of 0.29 and 0.32 were respectively yielded. The existence of difference in proportion factor for Newcastle as compared to ports consisting of ship sizes of <2499 TEU only, could be justified based on the errors yielded during the investigation. Although the difference in proportion factor is rather insignificant, where calculated to be 0.01, it was not ignored and an analysis was performed. It was discovered that error occurs for ports with a small vessel count, which in this case was identified in Newcastle, where the exporting container ship count ranges from six to seven annually. Therefore, it should be noted that the number of vessels exporting would affect the accuracy of the estimation.

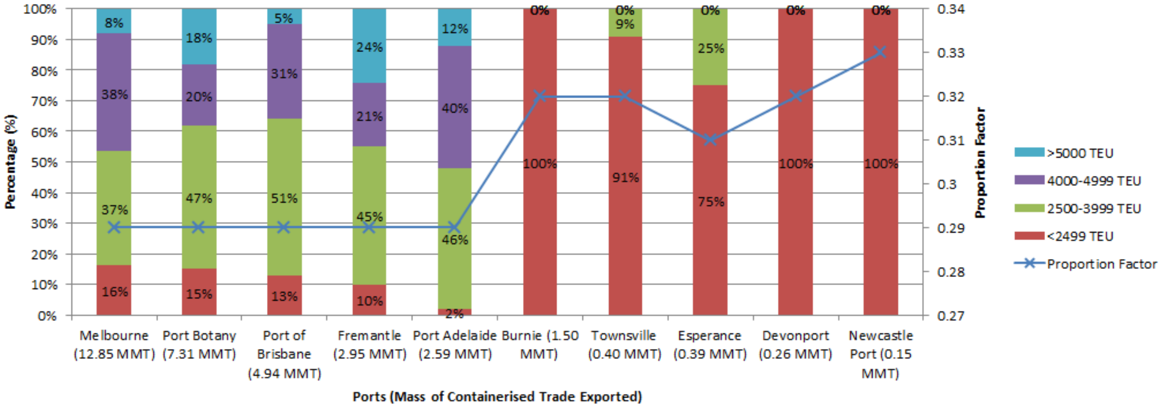

Figure 7: Container ship size proportion with resultant proportion factors

4.2 Bulk Carriers

Unlike container ships, bulk carriers are complex as their sizes were categorised into six categories instead of four. Similarly, the top 10 ports exporting bulk cargoes were identified and vessel counts, the varying ship size proportions along with the resultant proportion factors for each port are plotted in Figure 8. As clearly observed on the left hand side of Figure 8,the number of Capesize vessels has a strong influence on the proportion factors. It is evident that a decrease in the number of Capesize vessels exporting goods would decrease the proportion factors. This is marked in the comparison between Port Hedland, with 65 percent of vessels sized at Capesize and Newcastle at 22 percent, where the proportion factor differed by 0.07. Another aspect that affects the proportion factor, however less obvious, would be the increased proportion of Handy sized vessels.

Comparing Fremantle, handling 51 percent of Handy sized exporting vessels, with Geraldton at 20 percent, the proportion factor has increased by 0.03.

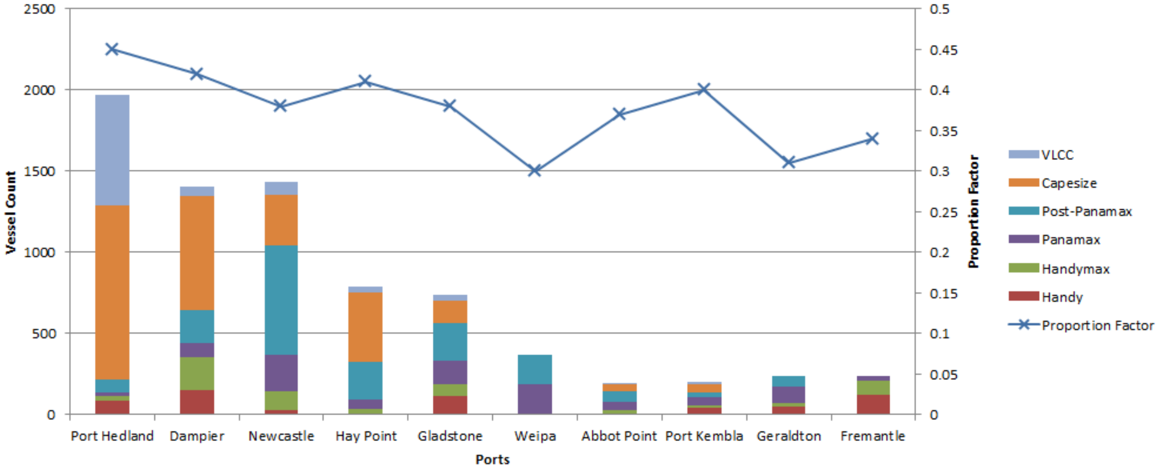

Figure 8: Bulk carriers size proportion with resultant proportion factors

4.3 General Cargo

The estimation for general cargo ships was performed differently, as mentioned previously in Section 2.2.1. Instead of being classified into size categories, the average deadweight was taken. Figure 9 depicts the top five ports exporting general cargo with the individual averaged deadweight and the yielded proportion factor. The prominent relation established was the increase of proportion factor as ship size decreases. Where the total mass of freight exported is equivalent, the frequency of vessels exporting increases as the size of vessel decreases, thus causing the quantity of ballast water discharged to be larger. This is evident in the comparison of the two extremes, Port of Portland and Dampier, where the difference of proportion factor is 0.53.

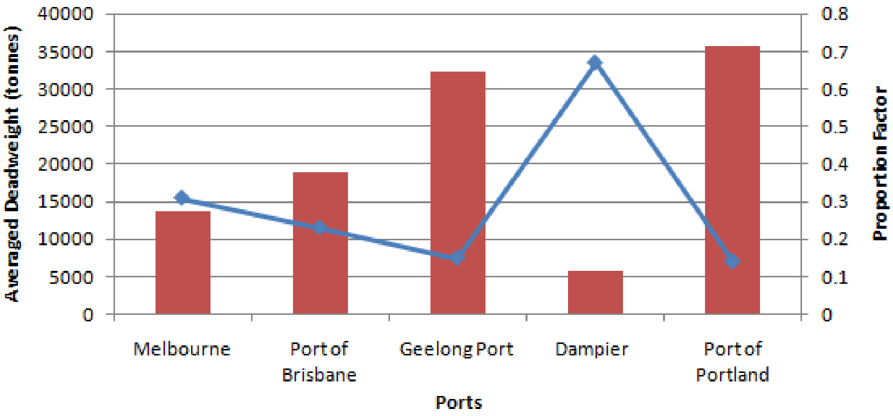

Figure 9: Averaged deadweight for general cargo ships with resultant proportion factors

4.4 Comparison between Methodologies

Due to the abundance of detailed trade statistics data provided by Port Hedland, two separate methodologies were utilised in the estimation. The provided statistical data show the type and weight of commodity exported and the deadweight for individual vessels. Five years of data were collected and the exporting ships were classified into their respective type and size. It is important to note that the main commodity exported from Port Hedland is iron ore, which is exported by bulk carrier[14]. Commodities exported by other ship types such as container and general cargo ship were insignificant, and thus excluded in the estimation.

The first method, Method 1,employed the same approach as applied in other study of ports. The total mass of freight exported was identified and the number of ships was calculated. The ship size proportion was determined based on data collected for one financial year. Conversely, the determination of ship size proportion was excluded in Method 2, which instead takes advantage of the detailed data that were provided. After the classification of individual vessel types and sizes, the vessel count for each size category and type were determined.

The amount of ballast water discharged was then estimated for both methodologies and a comparison was performed. Figure 10 plots the ballast water discharged yielded in the estimation for both methods, the mass of bulk cargo exported, and the respective proportion factors calculated for five financial years. Both methods show similar trends in the amount of ballast water discharged when compared to the mass of bulk cargo discharged. However, it is evident that an error between Method 1 and 2 exists and should be further analysed.

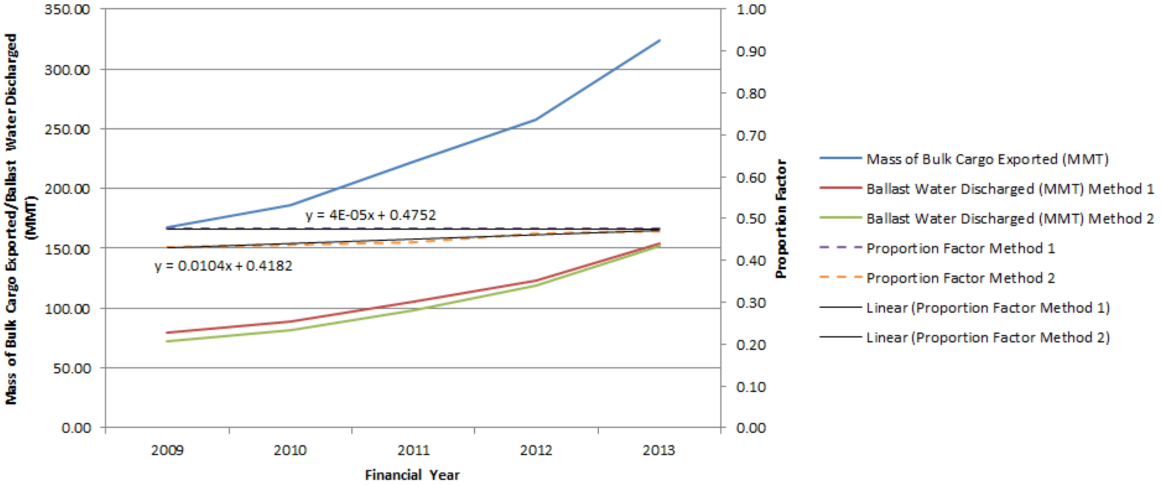

Figure 10: Comparison between Method 1 and 2

The analysis of the yielded error between both methods was performed and led to the formation of

Table 4. Method 1 in comparison to Method 2 showed consistency in the calculated proportion factor whereas Method 2 yielded varying proportion factors ranging from 0.4513 ± 0.02. This is expected as Method 1 utilises the same ship size proportion throughout the five years. The percentage error between the methods was determined and the maximum error yielded was 4.39 percent.

Table 4. Percentage error between Method 1 and Method 2 for respective financial years

Financial Year	Proportion Factor		Percentage Error (%)
	Method 1	Method 2	
2009	0.4752	0.4312	4.39
2010	0.4754	0.4388	3.67
2011	0.4751	0.4430	3.21
2012	0.4752	0.4625	1.26
2013	0.4755	0.4713	0.42

4.5 Comparative Study of Previous Models

Comparatively evaluating the methodologies adopted by previous works, the analysis has questioned the accuracy of the Brisbane model that was produced by Dunstan & Bax[7]. The model was established based on the relation where the ballast water discharged can be estimated by multiplying the deadweight sum of all ships by 38 percent. Additionally, a similar assumption was made within the estimation conducted by Kern and Stuer-Lauridsen[9], conducted in Danish waters. They state that 'any loading operation leads to a ballast water discharge of 30 percent of the cargo loaded'. For similar reasons, the statement reveals a discrepancy within the estimation.

Table 5. Models with resultant ballast water discharged

Model	Ballast Water Discharged (MMT)
Dunstan & Bax	12.69
Kern & Stuer-Lauridsen	8.99
Developed Model	14.26

A comparative study was conducted to verify the accuracy of the Dunstan and Bax and the Kern and Stuer-Lauridsen models, in comparison to the developed model. Data collected from Port Hedland for December 2013 was utilised and set as a constant for the investigation. Here, a total mass of 29.95MMT, solely on dry bulk, was exported and a deadweight sum of 33.39MMT for bulk carriers was calculated for this particular month. It was also discovered that 88.46 percent of bulk carriers consisted of Capesize and VLCC vessels[14].

Table 5 shows the estimated amount of ballast water discharged based on the individual model employed. In examining the results yielded, it is evident that both of the earlier models underestimate the magnitude of ballast water discharged in comparison to the amount estimated by the developed model. To further clarify the errors yielded by both models, a relation between specific ship sizes and the estimated amount of ballast water discharged for each model was established and is shown in Figure 11. Based on the graph, a distinct dissimilarity in trend between both the Dunstan and Bax and the Kern and Stuer-Lauridsen models, when compared to the developed model, can be inferred. The Dunstan and Bax and the Kern and Stuer-Lauridsen models yielded a linear trend, whereas the developed model resulted in a significant exponential trend. Both of the earlier models begin to underestimate the amount of ballast water discharged as the ship size increases to Capesize vessels. This relation justifies the underestimation as established in the results presented in

Table 5, when compared to the developed model.

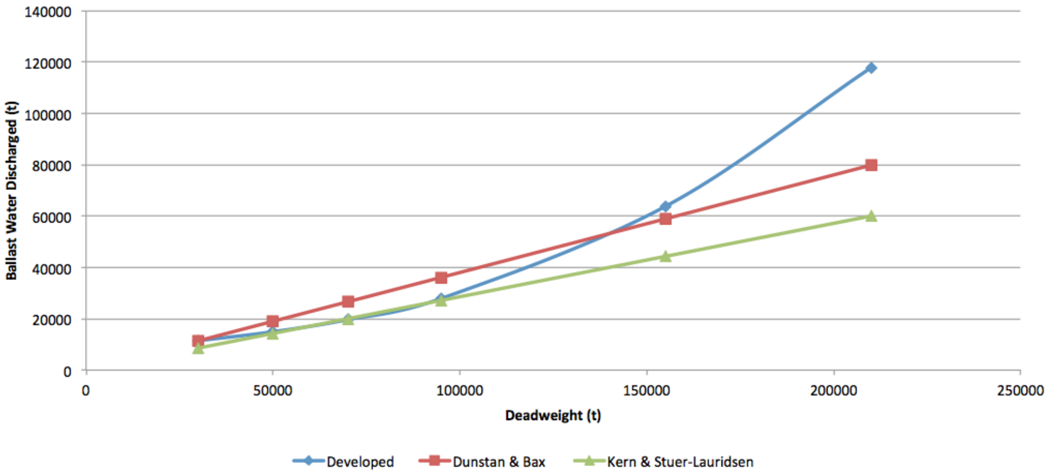

Figure 11: Ballast water discharged based on varying ship sizes for individual models

As previously discussed in Section 3.2, it was established that varying ship types also affects the amount of ballast water discharged. This is evident in Table 3, but it is not an issue that was taken into account in the Dunstan and Bax and the Kern & Stuer-Lauridsen models. Therefore, the assumption that all ship types would discharge the same amount of ballast water questions the accuracy of the estimates yielded by Dunstan and Bax and by Kern & Stuer-Lauridsen and in turn undermines the validity of their models.

5 CONCLUSIONS

Ship-mediated bioinvasion, specifically through ballast water, imposes risks that should not be overlooked. Through the investigation undertaken, it is evident that the amount of ballast water imported to Australian ports is increasing from year to year. The increment is apparent when comparing both years 2009 and 2013, where the amounts were estimated at 275.50 MMT and 414.66 MMT respectively. In a period of five years, an increment of approximately 50 percent was discovered and this amount would indefinitely continue to increase.

Locations of high risk imposed by ship-mediated bioinvasion were indicated at the north-west of Australia. It was estimated for the year 2013 that 60 percent of Australia's total amount of ballast water was discharged in Dampier and Port Hedland. The study conducted has also revealed that approximately 94 percent of ballast water was mediated through bulk carriers. This underlines the dominance of freight exported by bulk carriers in Australia.

To ease predictions in quantifying ballast water discharged, proportion factors for individual ship types were produced during the study. Consequently, it is recommended that these proportion factors are to be used for rough predictions only. Proportion factors established were found to be highly dependent on the varying ship sizes. A comparison between two methodologies was conducted, where detailed statistical data from Port Hedland was utilised in Method 2,and Method 1 was an approach employed for the study of other ports. An acceptable percentage of error was yielded between the resultant proportion factors for both methodologies, thus estimations implemented for the ports would generate results of high accuracy.

5.1 Recommendations and Future Research

As concluded by most research regarding the estimation of ballast water discharged, the quantity of detailed data governs the measure of parameters that could be taken into consideration during the creation of a model. It is evident that an increase in the parameters included in the estimation would generate results of higher accuracy. Correspondingly, the investigation undertaken for Australian ports would yield better estimates with the accumulation of further detailed data.

In the investigation, the amount of ballast water discharged from general cargo ships, LNG/LPG, livestock and vehicle carriers were estimated based on the averaged deadweight calculated for individual ports. To further improve the accuracy of the estimation, a methodology into the classifications of ship sizes for these ship types should be developed. Additionally, the sensitivity of the resultant proportion factors based on alterations made to the selected deadweight for individual ship types and their respective size categories should be examined. The selected deadweight that was used in the investigation was shown in Table 1 for tankers, bulk carriers and container ships. If other ships types were to be classified based on their sizes as well, a sensitivity analysis is recommended.

The study has established the locations and magnitude of ship-mediated bioinvasion risk in Australia. In order to mitigate such risks, a continuance of research into the identification of locations, as to where the origin of the ballast water is imported from, would be required. Furthermore, based on the origin of the imported ballast water, the specific species of mediated marine life should be investigated.

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