Carbon Emissions from Dredging Activities in Land Reclamation Developments: The Case of Jakarta Bay, Indonesia

N. S. Slamet[1, 3 *], P. Dargusch[1], D. Wadley[1], and A. A. Aziz[2]

[1] *School of Earth and Environmental Sciences, The University of Queensland, Steele Building Room 318A, St Lucia Qld 4072, Australia*
[2] *School of Agriculture and Food Sciences, The University of Queensland, St Lucia Qld 4072, Australia*
[3] *Ministry of Public Works and Housing, Jakarta 12110, Indonesia*

ABSTRACT. Plans for land reclamation across Indonesia will involve four to fourteen times the country's total 2015 sand consumption. The impacts of marine and estuarine dredging to supply major projects of this type have been neglected in carbon accounting to date. This article provides a preliminary estimate of the operation and emissions of various Trailing Suction Hopper Dredgers (TSHDs) in extracting material from quarries and depositing it to appropriate sites. Four phases of the dredging cycle and speed-power proportions from maximum engine capacities are simulated to obtain the total and per phase emissions. Sailing contributes most (37 to 55% of the total dredging) emissions, but also exhibits significant variability compared with other phases. Decreases in the speed-power proportions lower emissions, but increase the overall dredging duration. Sailing emissions can be reduced markedly by restricting the travel distance between quarry and reclamation site.

Keywords: emission, land reclamation, sand mining, trailing suction hopper dredger.

1. Introduction

In emerging nations, economic development coupled with population growth has accelerated the demand for resources (Harrison et al., 2005; Lu et al., 2007; Padmalal and Maya, 2014). Worldwide, the utilization of materials in 2017 was 3.4 times that of 1970 (Oberle et al., 2019). Non-metallic categories, such as soil, cement, sand and rock, are the fastest-growing, surpassing fossil fuels, metal ores and biomass. The proportion of non-metallic within total material consumption rose significantly from 34% in 1970 to 48% in 2017 (Oberle et al., 2019). The Asia Pacific region doubled its usage of the global total from 24.3% in 1970 to 52.9% in 2010 due to its rapid advancement (Schandl et al., 2016b).

Many countries have difficulty in meeting their material requirements from local supply and, in order to cater for the demand, importing has become more common. Global imports grew significantly in the last four decades, from 2.6 billion in 1970 to 11 billion tonnes in 2010 (Schandl et al., 2016a). Yet, greater volumes and distances travelled have lowered operational efficiency. Given the global shift since 2000 of economic activity from highly to less efficient countries, more materials have been needed per unit gross domestic product (GDP). The

Asia Pacific region has been the main source for Europe and North America, making its per-capita material footprint only half that of Europe and one-third that of North America (Schandl et al., 2016a). Yet, with more materials involved, utilisation for construction or production processes is increasing emissions (Torres et al., 2017).

Land reclamation occurs globally to support city development. It involves massive quantities of sand (Larson, 2018). The reclamation islands in Dubai required an astonishing 1.74 billion cubic metres (m³) (Pronk and Lindo, 2005). The push for proposed new landmasses is growing, although environmental concerns have emerged from development and sand mining (Harrison et al., 2005; Padmalal and Maya, 2014; Griggs, 2017; Larson, 2018).

Sand utilization contributed 31.1% of global total non-metallic material consumption in 2010 (Schandl et al., 2016a). The actual quantity involved is four times that consumed in 1970. In Indonesia, the volume demanded remained above 250 million m³ for five years after 2011, reaching a maximum of 376 million m³ in 2015 (Nuryati and Faradila, 2016). Most is used in construction. Yet, infrastructure development, fostered by the current President to boost economic growth, is co-opting still more material. With a plan to reclaim 244 km² of its coastal region for new development, Indonesia will need a far greater supply. The shift in the use of sand from building and construction activities to land reclamation is ongoing.

Worldwide, the majority of the sand for construction is extracted from rivers. For high quality (prestressed) concrete, rock-

* Corresponding author. Tel.: +61-7-3365-6455; fax: +61-7-3365-6899.
E-mail address: n.slamet@uq.edu.au (N.S. Slamet).

based products delivering manufactured sand are used. For land reclamation, by contrast, most materials are derived from the coastal area, from shallow or deep sand mining.

Sand mining is conducted with various types of dredging vessels. It can lead to a rise in political tension between exporter and importer countries (Torres et al., 2017). Impacts occur at the quarry, the deposition site and along the transport route. Effects can be assessed in changes in the surrounding physical (Guo and Jiao, 2007; Baolei, 2012; Wang et al., 2015), chemical (Wang et al., 2014) or biological environments (Suo et al., 2015; Duan et al., 2016). Carbon emission along the transport route is considered a spillover effect of mining (Torres et al., 2017).

Though widely overlooked, marine dredges are, of course, a form of shipping. Conventional shipping output fell from 3.5% of total global emissions in 2007 to 2.6% in 2015, that is, from 1,100 to 932 Mt CO_2 (Olmer et al., 2017). Although shipping is considered a low-rated activity compared with other transport modes, its emissions were notably greater than those of aviation which, in 2013, contributed 1.9% (Gausel, 2014).

Dredging vessels have been excluded from the shipping and heavy machine emission counts. While ships of different classes are known to produce 73 ~ 92% of their emissions from sailing (Olmer et al., 2017), TSHDs not only sail but engage in significant extra energy use also producing emissions (Castro et al., 2014). Information about their operation and outputs is scarce. Understanding the dynamics of their respective phases is important to develop appropriate action to minimize pollution.

The life cycle of a dredging vessel consists of its production, operation, maintenance, and disposal. Emissions from operations account for 99.53% of the life cycle assessment (Castro et al., 2014). This study aims to investigate the production of greenhouse gas (GHG) created by dredging fleets featuring different speeds, hopper volumes and distance travelled in supplying material for coastal land reclamation. Accurate estimation is needed to complement emission data from shipping or terrestrial construction. The case of a major land reclamation in Indonesia provides ready opportunities for analysis via simulation.

2. Materials

2.1. Land Reclamation in Indonesia

Within Indonesia's plan for additional coastal landmass, one of the areas most implicated is the Jakarta Bay Land Reclamation, with 5100 ha of new islands on the drawing boards (Indonesian Ministry of Ocean and Fisheries, 2018). The project is located north of Jakarta, spreading east to west from the Babelan to Kamal sub-districts. It requires a large material volume which comes from the western coastal area, at distances ranging from 47 ~ 260 km (Figure 1). The quarry is a coastal zone, regulated for sand extraction, in the province neighbouring Jakarta. The location includes shallow areas and nearby beaches. The depth of the quarry is approximately 20 m, with the available sand within 1 ~ 8.7 m from the ocean floor. Globally, dredging depths are classified as below 130 m and between 130 ~ 3,000 m, termed offshore mining and deep-sea mining, respectively

(Ehab Elsayed, 2013). The Indonesian site thus represents offshore mining.

In total, approximately 109 million m^3 of sand are required to complete five islands in Jakarta Bay, one-third the total volume consumed in Indonesia in 2015. The quarries in the present analysis are distinguished in term of area, available dredging depth and volume. The quarry area, material type, and depth of dredging are analysed according to the Environmen-tal Impact Assessment (EIA) of the reclaimed islands, but we remark from the outset that its assumptions will result in lower simulation results compared with actual emissions. As an offset, however, this study has advantages in comparing the performance of different vessels and operational methods.

2.2. Utilization of TSHDs

A TSHD is a vessel designed to dredge and transport material independently from quarry to construction site. It is capable of extracting various soil fractions from mud to gravel from a large range of depths. In addition to the dredging capacity, a hopper container is installed to store extracted spoil and transport it to a designated site. That place can be near shore or inland, with subsequent movement required for the latter. Road transportation can be engaged in such instances.

Dredging, transporting, and unloading material presume considerable power and a large amount of fuel oil. Due to the voluminous material, the dredging cycle must be repeated many times to supply a land reclamation. Considering the cycle characteristics of TSHDs, the loading and unloading phases do not vary much, since the pump system, pipelines and hopper size are proportionally designed. The loading phase is affected by the area of the quarry, material type, depth of dredging, wind and currents condition (Shi, 2013). Transportation demands rise with the distance to be travelled. Unloading is subject to weather conditions, material type, wind and currents. The methods include bottom door exit, rainbowing or pumping ashore. Wind and current are assumed to be constant in the simulation of different methods, while unloading depends on the vessel specification. The performance of vessels can be simulated via all three unloading methods.

Dredging vessel data are obtained from the International Association of Dredging Companies (IADC). There are 82 dredging vessels registered worldwide with the Association, ranging from 966 to 46,000 m^3 in hopper volume. Among them are 31 reclamation dredgers having hopper capacity above 12,000 m^3 (Ouwerkerk et al., 2007). The designed power output varies from 6,676 ~ 41,665 kW.

2.3. Sand Mining Area and Distance

Jakarta's coastal sand mining areas are located in the northern Banten Bay and the offshore Bangka Belitung area. In total, quarries registered for the reclamation contain 190.76 million m^3 of sand. The area covers eight sites with available material varying from 2.5 to 60 million m^3 (Figure 1). The mining areas beyond 85 km, namely LIP, CHA and WTB are not mapped in Figure 1.

For simulation, distance from a quarry to a reclamation site is a key consideration. Each time an area is fully dredged,
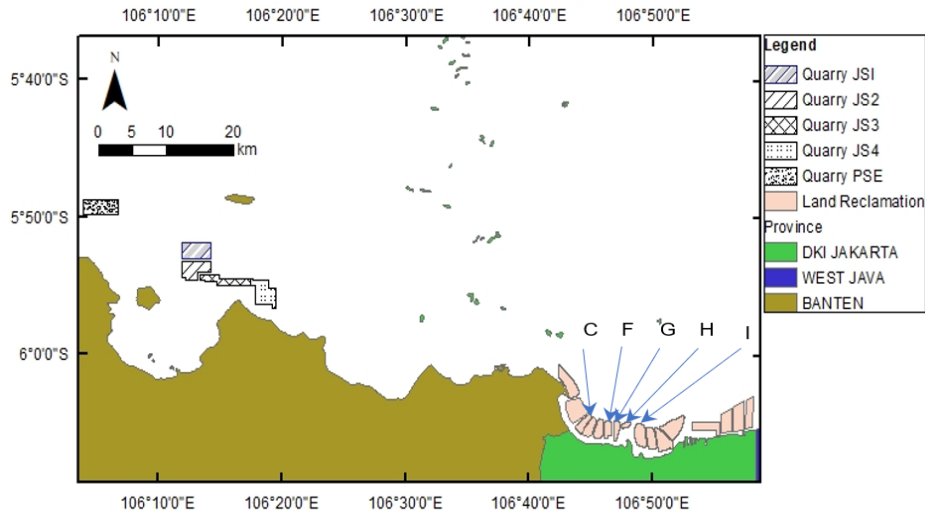
Figure 1. Quarries and reclamation site (compiled from the EIA of reclaimed islands).
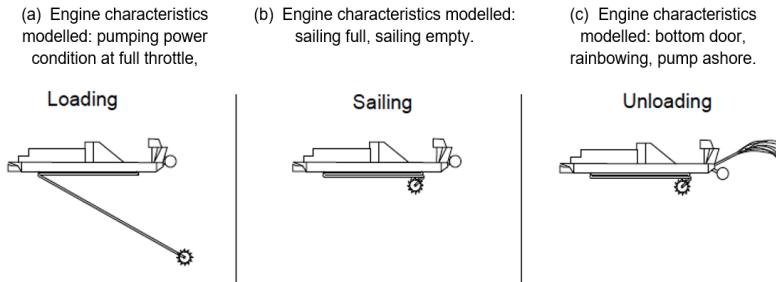

Figure 2. The characteristics of TSHD phases: (a) loading; (b) sailing; (c) unloading (Bray, 1979).

a change is made to the next closest quarry. The dredging cycle is completed when the required material for constructing a new island is supplied. Analysis for the next island is based on the precept that it has not yet been reclaimed. This assumption exists so as to maintain the dredging areas as a constant parameter during the simulation.

Table 1. Islands' Material Requirements

Island	Sand Volume (m³)	Area (ha)	Sand Material/Area (m³/ha)
C	18,663,055	285	65,484
F	25,000,000	190	131,579
G	10,600,000	161	65,839
H	11,600,000	63	184,127
I	43,154,877	202.5	213,111

Note: EIA of reclaimed Islands (Susanto et al., 2012; Afiff et al., 2013; Priatna et al., 2014; Suriadi et al., 2014; Susanto et al., 2015).

Distance from the quarry to the reclamation site varies from 47.43 to 258.18 km. The extraction of material is sequenced from sources JS4, JS3, JS2 to WTB until volume requirements are met. In the simulation, the material extraction for Island I comes from five sources to PSE, while the other islands' utilization only involves up to source JS1 (Figure 1).

2.4. Sand Requirement

The mass of sand needed to complete each island varies (Table 1). The lowest quantity occurs in the Island G operation, 10 million m³ for the 161 ha reclaimed (Table 1). Island I requires the most (43 million m³) for its 202.5 ha, and also, with 213,111 m³, represents the largest amount of material per hectare of reclaimed land. A similar amount per hectare is required for Islands C and G, each needing approximately 65,000 m³ of sand (Table 1).

3. Methods

3.1. TSHD Characteristics

Coastal dredging equipment, notably the TSHD, is differentiated from shipping fleets by its additional large pumping engine. During the working cycle, there are four phases in the loading/engine operation characteristics. The first is sailing empty (from a reclamation site) to the quarry; second is extracting material (loading); third is sailing a full load back to the site; and the last is unloading. General shipping fuel characteristics require further adjustment in application to dredging vessels. The TSHD work cycles are a key factor in simulating the power and emissions from dredging (Cuyper et al., 2014).

Each one generates different engine and power load char-

acteristics (Figure 2). During the unloaded sailing, weight is at its lowest, speed greatest. Loading of the material requires high power to the dredging pump operation with slow manoeuvring speeds. Sailing the full load from the quarry to the reclamation site assumes high power from the vessel's engine. Of the three ways to discharge the material from the vessel, bottom-door dumping consumes the lowest power and is quickest, taking only 5 ~ 10 minutes. Rainbowing and pumping ashore require longer periods, and more power. We estimate 1.5 hours for rainbowing and one hour for pumping ashore (Bray, 1979).

The low power and faster time of bottom door discharge are available for all TSHDs. However, not all are equipped with all three unloading methods: some can only discharge via the bottom doors. The bottom door method generates higher turbidity from discharging a large amount of material over a short period, but it falls away with distance from the receiving site (Cutroneo et al., 2012). The turbidity impact of the TSHD is approximately 50 ~ 150 mg/L (Ehab Elsayed, 2013). The distance from the new islands to the northern Jakarta coast is regulated to exceed 300 m, so as to minimize turbidity of coastal waters.

3.2. TSHD Phases

Dredging power output is calculated based on the TSHD's design power and dredge duration to extract the required material. Dredging routes, turning, and type of material are fundamental factors in the calculation of generated power during loading.

Dredging vessels are excluded from IMO global GHG emissions. Although they make up a small proportion of the entire shipping fleet, TSHDs have a significant impact on the environment. The vessel is a fusion between a heavy machine and a large ship. For sailing speed and power generation characteristics, the United States Energy Information Administration (USEIA, 2015) offers an approximation for census divisions across America for different type of vessels, from tankers, container ships, gas bulk carriers, ferries, commodity carriers, and on to general cargo freighters.

To complete the TSHD's dredging cycle, simulated phases of work involve loading, turning, sailing and dumping (Figure 2). Hopper capacity and efficiency are simulated according to the formula developed by Bray (1979). Each phase of work is individually examined according to the TSHD's specification and power capacity.

3.3. Loading

Loading time is similar regardless of the hopper capacity, due to the proportional design of the hopper with the pumping system. Loading time is dependent on soil type and the overflowing mechanism of the hopper. Informed by the Indonesian Environmental Impact Assessment (EIA) of the reclaimed islands, static parameters are assumed for the quarry area, soil type, wind, current, wave height, the transportation route and fuel type. The variable parameters are hopper volume, speed, power and speed-power proportion.

The load during the dredging cycle activity is considered as a dynamic behaviour engine characteristic (Shi, 2013). It is influenced by waves, wind speed, weather, vessel speed, pumping discharge, ship design and material properties (Castro et al., 2014; Cuyper et al., 2014). However, constant engine speed is used in the simulation, since real-time measurement is needed to simulate the dynamic behaviour. The total power production of the engine can be generated with constant speed by assuming specific dredge conditions (Shi, 2013). In this analysis, a specified maximum continuous rating (SMCR) is used. The bulking factor for medium soft to hard sand is in the range of 1.15 ~ 1.25 (Bray, 1979). A median value of 1.2 is used in the calculation of dredging operations.

The EIA offers information on waves, currents and winds. The dominant wave height was 0.75 ~ 1.5 m from northeasterly and northerly directions. The current condition was dominated by a westerly or easterly orientation with speeds of 0.1 ~ 0.4 and 0.2 ~ 0.5 m/s, respectively. Wind direction and speed were predominantly from the north at 3.35 ~ 5.45 m/s (Susanto et al., 2012; Priatna et al., 2014). The dominant values do not provide any serious constraints (EPA, 1993).

3.4. Turning

Dredging activity is controlled in the permitted mining area, and turning occurs each time the dredge reaches the boundary. Turning is considered non-productive time. The number of turns per cycle is calculated by the identity $6.84 \cdot t_l/l$ and turning time follows $6.84 \cdot t_l \cdot t_l/l$. In these computations, t_l = loading time (hours), following Bray, page 118 (Bray, 1979), l = dredging area length (km), and t_t = time to turn at the end of dredging area (hours).

The sailing speed of TSHDs when unloaded varies from 9 to 17 knots (16.7 ~ 31.5 km/h). When fully laden, their design speed ranges between 7 and 16.2 knots (13 ~30 km/h). Speed calculations for the simulation are estimated from the TSHD's design speed.

Sailing from quarry to the deposition zone is assumed to follow a straight line. Although this condition is unrealistic due to established shipping lanes, it is the appropriate way to compare different vessels and quarry sites. Sailing time from the quarry to the deposition ground and back is computed as $1.02 g/V_g$, with 'g' the distance between the quarry and the site (km) and V_g the sailing speed (in knots).

3.5. Dumping

Admitting excess water optimises hopper volume. Overflowing water increases turbidity but offers higher TSHD efficiency. Without overflowing, only 30% of maximum hoper capacity can be engaged to transport material (Been et al., 2012). In the simulation, an overflowing facility is assumed.

Specification for bottom door power is unavailable from the IADC list of TSHDs. Following a reference from the International Maritime Organization (IMO, 2015), auxiliary power demand is set at 5% of the installed power of the TSHD. For other dumping methods, energy utilisation is similar to loading with the same pump.

Table 2. Speed-Power Proportion of Ships (USEIA, 2015)

Speed and Engine Power Combination			
Percentage of Design Speed	Percentage of Design Power	Census Division	Ship Type
83	60	New England, Middle Atlantic, South Atlantic, East South Central, West South Central, Pacific, Puerto Rico.	Tankers, Container ships, Gas Bulk Carrier, Ferries, Commodity Carriers, General Cargo.
82	59		
82	58		
81	57		
80	55		
78	51		
76	**49**		
73	45		
70	39		
68	36		

3.6. Approximating Emission Output

The estimation of gaseous emissions from dredging activities in the Jakarta Bay land reclamation follows the USEIA (2015), IMO (2015) and International Council of Clean Transportation (ICCT) approximations (Olmer et al., 2017). Emissions generated by the movement of TSHDs from any previous project to the current site are excluded from the analysis. Our emission simulation does not incorporate in situ land development activities, such as piling and bulldozing. The calculated emission is generated purely from sand mining and transportation to supply the material.

The total energy consumption in conducting one dredging cycle is a combination of all four phases. The total material requirement divided by the capacity of each dredging cycle signifies the total cycle number. The total number of cycles times the energy consumption from each cycle represents the total energy consumption to supply land reclamation:

$$E_c = E_l + E_{sf} + E_d + E_{se} \tag{1}$$

$$C_n = Material_r / C_c \tag{2}$$

$$E_t = C_n \times E_c \tag{3}$$

where E_c = energy to conduct one dredging cycle (kWh), E_l = energy consumption from loading (kWh), E_{sf} = energy consumption from sailing full (kWh), E_d = energy consumption from dumping (kWh), E_{se} = energy consumption from sailing empty (kWh), C_n = number of cycles, $Material_r$ = material requirement to supply reclaimed island (m³), C_c = dredging cycle capacity (m³), and E_t = total consumed energy to complete the material supply (kWh).

Fuel data from coastal dredging activities are not available from the Jakarta Bay Land Reclamation report. An estimation of power output based on the four cycles of dredging activity, distance travelled and required material volume is compiled according to the TSHD's specification. Ship-optimised engine loads in sailing are 70 ~ 85% of the maximum design speed (IMO, 2015). The USEIA (2015) has recorded vessels' speed-power proportions for various ship types across American census divisions (Table 2).

The recorded ships' speeds range from 68 ~ 83% of the design speed. The actual speeds require 36 ~ 60% of the maximum installed power. Values of 76% in ship speed and 49% of power consumption are obtained by averaging the recorded speeds and power generation from all available census divisions and ship types. Simulation of the operating speed and engine power is conducted for all selected speed-power scenarios (Table 2). The average speed-power setting of 76 for 49% is used in the following discussion.

3.7. Conversion of Fuel

Fuel consumption per kWh of engine usage for each TSHD depends on the age of the vessel. The chronology of TSHD manufacture falls into three periods: before 1983; 1984 ~ 2001; and after 2001. Each record different fuel weight per kWh. Before 1983, the level is 205 gr/kWh; 1984 ~ 2001 posts 185 gr/kWh; while, after 2001, the ratio falls to 175 gr/kWh (IMO, 2015; USEIA, 2015). An auxiliary engine consumes 225 g/kWh (IMO, 2015). As a result of lower fuel consumption, newer vessels emit less pollution compared with older ones.

Generated power for each phase is converted to fuel consumption for each dredge. Fuel consumption, per phase and in total, is analysed for each vessel together with distance from the quarry to the deposition site.

3.8. Emission Conversion

A diesel engine emits various chemical gases during operation, from acetaldehyde to xylenes (Mark, 2008). The emissions selected for the present analysis are CO_2 (carbon dioxide), CH_4 (methane) and NO_x (nitrogen oxides), which represent the common parameters in greenhouse calculations (IPCC, 2019). NO_x gas plays diverse roles, since it has both advantageous and adverse impacts on the environment. Its forms ozone with solar and other volatile compound reactions, forms acid elements, reduces visibility, boosts algae bloom and contributes to climate change acceleration (EPA, 2020). The conversion of fuel consumption to emissions is undertaken according to the

following formula (IMO, 2015):

$$E_{ij} = Q_i \times EF_{ij} \tag{4}$$

where E_{ij} = emission gas type (j) according to fuel type (i), Q_i = fuel quantity (tonnes), and EF_{ij} = emission factor for each gas type (kg).

An emission factor corresponds to the type of fuel, any engine modifications, and possible exhaust treatment installations (IMO, 2015). Engine modification, and exhaust gas treatment data are unavailable from the IADC list of TSHD vessels. Each method is designed to lower a specific type of gas emission. In the calculations, engine and gas treatment modification is neglected during operation. The engine and exhaust are assumed in accordance with the standard manufacturer's specification. The emission factor for each gas type is calculated according to the IMO report of 2015 with marine diesel oil (MDO) as the fuel type.

The emission factors respectively for CO_2, CH_4 and NO_x are 3.206, 0.06, and 0.15 g/g fuel (IMO, 2015), follow Equation (4). IMO specifications for those gases are constant over time. Simulated fuel quantity according to the dredging phase is then converted to estimate emissions for each vessel and speed-power proportion.

4. Results and Discussion

The nominated power proportion, 49%, falls outside the IMO's optimum operational ship ratio of 65 ~ 80% of SMCR (IMO, 2015). This average is nonetheless used in the analysis. The other simulated results will be covered later in comparison with the 76 ~ 49% speed-power proportion. Those speed-power proportion results can be found in Appendix Table S1.

Total emission is that generated from conducting sand supply operations for construction of each island. It is derived from the number of cycles to dredge-transport-deposit material from quarry to site, back and forth. The number of cycles and power is converted to fuel and emissions according to each TSHD's characteristics and chosen method of loading.

Result are presented in the following sequence: total emissions; emissions per phase; emissions per m^3 of material; emissions per ha of reclaimed island; and emissions from different speed-power proportions. For total emissions, the three generated gas types are presented (CO_2, CH_4 and NO_x) while for other discussions, only CO_2 is analysed.

4.1. Total Emissions per Island

The available data from the Jakarta Bay land reclamation come from islands C, F, G, H and I, five out of 17 in total. The total generated power of dredging vessels to supply material varies from 10.5 to 406.24 GWh. Average values are 67.7 ± 42.7, 93.5 ± 59.5, 40.3 ± 25.8, 44.5 ± 28.5, and 168.2 ± 108.6 GWh for islands C, F, G, H, and I, respectively.

The generated power attributed to each island involves fuel consumption ranging from 1,834 ~ 71,092 tonnes. Island I demands the most, island G the least. The average fuel consumption is 12,079 ± 7,592, 16,689 ± 10,570, 7,201 ± 4,589,

7,936 ± 5,057, and 30,022 ± 19,310 tonnes to supply the material for Islands C, F, G, H, and I respectively (Table 3). Appendix Table S1 shows detailed comparisons among different speed-power proportions for each island.

4.1.1. CO_2 Emissions

Generated power is converted to emissions by multiplying it by the fuel consumption per kWh. Total CO_2 emissions per island from the operation of TSHDs vary greatly from 5,879 to 227,922 tonnes for the 76 ~ 49% speed-power proportion (Table 3). Via this proportion, the total outputs for islands C, F, G, H and I are 38,726, 53,504, 23,087, 25,442, and 96,252 tonnes respectively (Table 3). Islands G and H have lower total CO_2 emissions due to their needing less material for construction compared with the others. The standard deviation of the total CO_2 emission varies from 14,711 to 61,908 tonnes. It reflects the large variability in hopper volume, vessel speed and installed total power. For more information on emission effects influenced by hopper volume, see Appendix Table S2, which analyses each island given different speed-power proportions.

Slower sailing speed decreases total emission for all of the speed-power combinations. Greater sand requirements correspond to the larger standard deviation of total emissions. More operational time and TSHD cycles to furnish the supply generate more emissions and variation.

Comparing total CO_2 emissions occurring (laden) at 12 and 16 knots indicates that the marginal four knots increase their level twice that of the original 12 knots (Figure 3a). However, with slower speeds, a rise in sailing time occurs. It extends the overall project duration (further discussion is mounted in Section 4.4). On the other hand, an increase in emissions occurs following a decrease in hopper volume. Smaller hoppers, pro rata, emit more emissions than larger ones (Figure 3b). Increasing speed and smaller hopper volume create more emissions due to greater fuel consumption and energy production.

4.1.2. CH_4 Emissions

Besides carbon, the vessels of the fleet combust different types of gas. The total emission per island of CH_4 to supply material varies from 0.11 to 4.27 tonnes (Table 3). On average, sand mining to supply island I produces three times more CH_4 than the island C emission. The CH_4 emission from islands C, F, G, H, and I is 0.72 ± 0.46, 1 ± 0.63, 0.43 ± 0.28, 0.48 ± 0.3, and 1.8 ± 1.16 tonnes respectively.

The distance between islands C and I is 8.5 km, with Island C the closer to the quarry. island I requires 2.3 times more sand than island C. With further distance and a greater material requirement, CH_4 emissions rise. The proportion of the minimum to the maximum emission per island is, on average, 11%, given a hopper volume variation of 12,000 ~ 46,000 m^3, with loaded sailing speed ranging from 7 ~ 16.2 knots.

4.1.3. NO_x Emissions

Dredging vessels, in accordance with their design, emit significant NO_x gas ranging from 150.29 ~ 6,197.24 tonnes per
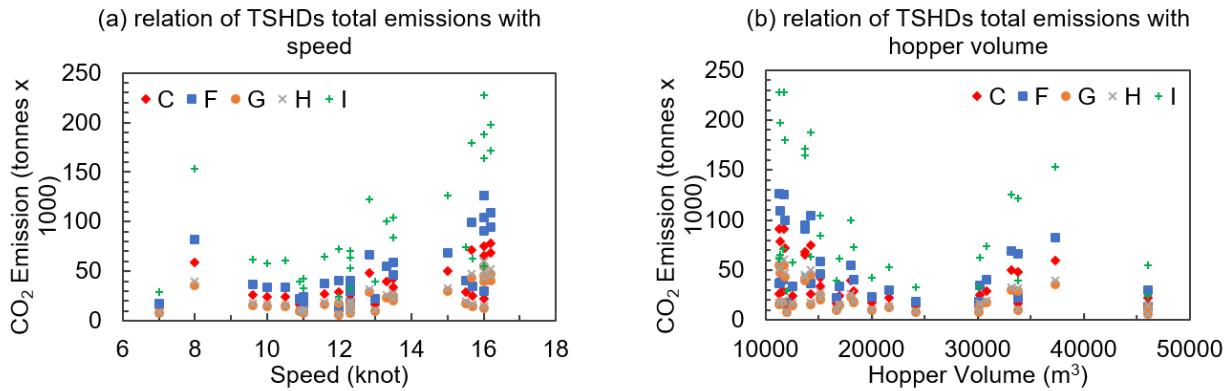
Figure 3. Total emissions of Trailing Suction Hopper Dredgers (TSHDs) for islands C, F, G, H and I (a) in relation to speed; (b) hopper volume.

Table 3. Summary of Simulated Trailing Suction Hoppe Dredges (TSHDs) Emissions

Island	Total Emissions			Emissions per m³ Material			Emissions per ha Reclaimed Island		
	CO_2 (tonnes) $\times 1000$	CH_4 (tonnes)	NO_x (tonnes)	CO_2 (kg)	CH_4 (kg)	NO_x (kg)	CO_2 (tonnes)	CH_4 (kg)	NO_x (tonnes)
C	38.73	0.72	990.52	2.08	38.83×10^{-6}	53.07×10^{-3}	135.88	2.54	3.48
	± 24.34	± 0.46	± 621.73	± 1.30	$\pm 24.41 \times 10^{-6}$	$\pm 33.31 \, 10^{-3}$	± 85.41	± 1.60	± 2.18
F	53.50	1.00	1368.45	2.14	40.05×10^{-6}	54.74×10^{-3}	281.60	5.27	7.20
	± 33.88	± 0.63	± 865.64	± 1.36	$\pm 25.37 \times 10^{-6}$	$\pm 34.63 \times 10^{-3}$	± 178.36	± 3.34	± 4.56
G	23.08	0.43	590.46	2.18	40.76×10^{-6}	55.70×10^{-3}	143.40	2.68	3.67
	± 14.71	± 0.28	± 375.76	± 1.39	$\pm 25.97 \times 10^{-6}$	$\pm 35.45 \times 10^{-3}$	± 91.38	± 1.71	± 2.33
H	25.44	0.48	650.69	2.19	41.05×10^{-6}	56.09×10^{-3}	403.84	7.56	10.33
	± 16.21	± 0.30	± 414.17	± 1.40	$\pm 26.16 \times 10^{-6}$	$\pm 35.70 \times 10^{-3}$	± 257.36	± 4.82	± 6.57
I	96.25	1.80	2461.68	2.23	41.74×10^{-6}	57.04×10^{-3}	475.32	8.90	12.16
	± 61.91	± 1.16	± 1581.93	± 1.43	$\pm 26.85 \times 10^{-6}$	$\pm 36.66 \times 10^{-3}$	± 305.72	± 5.72	± 7.81

* ($\pm$) signifies the standard deviation of the upper and lower values.

island. The average value varies greatly around 590.46 ~ 2,461.68 tonnes with a standard deviation from 375.76 ~ 1,581.93 tonnes (Table 3). The NO_x emissions from island C sand supply are 990.52 ± 621.73 tonnes, while islands F, G, H and I report 1368.45 ± 865.64, 590.46 ± 375.76, 650.69 ± 414.17, and 2461.68 ± 1581.93 tonnes respectively. The total NO_x emission is thus greater than that of CH_4.

4.2. CO₂ Emissions per Phase

Investigating CO_2 emissions based on the cycle phase of TSHDs indicates that sailing produces the highest overall contribution and displays a wider range of values compared with loading and unloading (rainbowing or pumping). Its emission value ranges from $0.18 \sim 3.15$ kg/m³; loading emissions range from $0.36 \sim 1.74$ kg/m³; and unloading (bottom door) emissions span 92.91×10^{-6} to 2.63×10^{-3} kg/m³ (from the Island C simulation).

Sailing is influenced by hull shape and dimensions. Optimising the sailing phase can follow from taking the shortest route, travelling at the optimum speed and considering weather conditions (Bouman et al., 2017). Sailing has an average emission value of 1.24 ± 0.91 kg/m³ of sand. The variation of the sailing emission value is twice the fluctuation of the loading

phase of 0.4 kg/m³ CO_2. Sailing also takes the longest time in the dredging cycle duration.

Sailing has the largest CO_2 emission proportion of the total (Figure 4a), even considering different unloading methods, ranging from $33.36 \sim 74.41\%$, $16.52 \sim 51.81\%$, and $18.92 \sim 54.3\%$, respectively for bottom door, rainbowing and pumping ashore. Those figures represent proportions of $54.91 \pm 10.68\%$, $37.07 \pm 11.33\%$, and $40.29 \pm 11.43\%$ of the total CO_2 emission (Figures 4b, 5a and 5b). The trend is similar for the other gases, CH_4 and NO_x.

Among 31 TSHD vessels suited to land reclamation along the Indonesian coastline, 10 have the ability to discharge material using the bottom door, rainbowing and pumping ashore methods. The other 21 can only discharge using the bottom doors. Five percent of the total installed diesel capacity is assumed for bottom door operation by consid-ering it as auxiliary power, with 225 g/kWh of MDO fuel con-sumption (IMO, 2015). The design of the pump and pipe for loading and unloading is proportional to the hopper capacity so that the duration is less varied.

Bottom door as the primary TSHDs discharging method has the smallest emission compared with rainbowing and pumping ashore. Among the 10 fully capable TSHDs, rainbowing

emissions range from 0.56 ~ 1.12 kg/m^3 while, for pumping ashore, the value lies between 0.42 ~ 0.84 kg/m^3. Average emission from rainbowing is higher compared with pumping ashore, 0.83 and 0.62 kg/m^3, respectively.
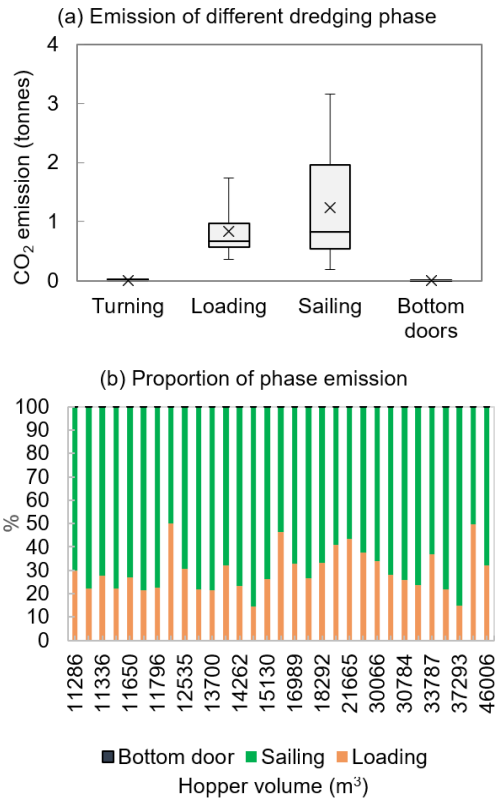

Figure 4. CO_2 emission per m^3 of material for island C for (a) different dredging phase, and (b) proportion of phase emission.

Among the three dumping methods, rainbowing has the largest proportion of total emissions per island ranging from 18.26 ~ 50.68% compared with pumping ashore at 14.35 ~ 43.52% (Figures 5a and 5b). On average, the proportion of total emissions is 34.32 ± 10.37% and 28.39 ± 9.26% for rainbowing and pumping ashore, respectively (Figures 5a and 5b).

4.3. CO_2 Emission per m^3 of Material

The total emission level divided by the volume of supplied sand indicates the emission per m^3 of deposited material. It thus reflects material efficiency. The minimum emission, controlled for different distances, varies from 0.54 ~ 0.57 kg/m^3, while the maximum ranges from 4.88 ~ 5.28 kg/m^3 (Table 3). A previous study reported 4 kg/m^3 (Ehab Elsayed, 2013) which is within the current range of 0.54 ~ 5.28 kg/m^3.

In general, greater distance from the quarry to the reclama-tion zone generates higher emissions (Figures 6a and 6b). Out-put per m^3 of material increases linearly with distance (Figure 7). Longer supply distances also enlarge the standard deviation of the emission. Since the increase in shipping cost from a fur-ther distance is unknown, road transport can be used as a proxy to

investigate how distance might affect cost and emissions. In such transportation, an increase in distance from 64.4 to 80.5 km doubles the cost of material (Padmalal and Maya, 2014). From such evidence, with the available quarries up to 260 km from the reclamation site, emission and cost will increase not linearly, but exponentially, with distance.
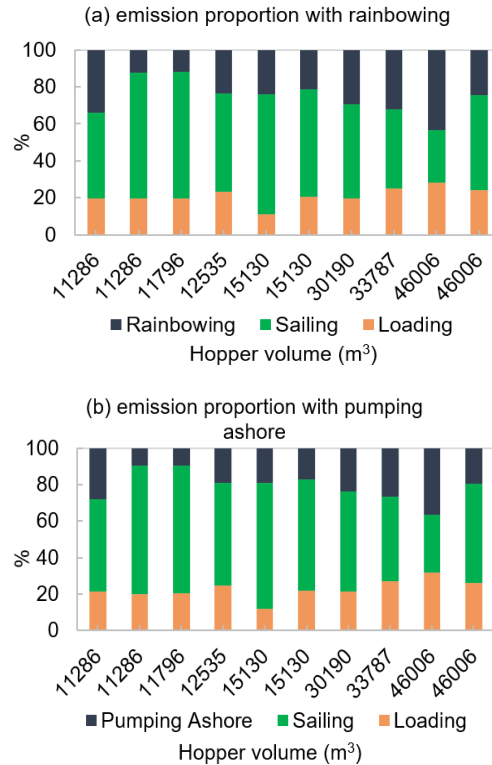

Figure 5. CO_2 phase emission proportion: (a) with rainbowing; (b) pumping ashore.

Average per m^3 of material emission of CO_2 varies from 2.08 ~ 2.23 kg and σ ranges from 1.3 ~ 1.43 kg (Table 3). The standard deviation enlarges with distance created by the geography of islands C to I. Comparisons for each island with various speed-power proportion are presented in Appendix Table S3. The level of emission rises with distance and engine power.

4.4. CO_2 Emissions per ha of Reclaimed Island

The requirement for material per hectare of reclamation differs according to the design and site condition of each island (Table 1). The largest is island C with 285 ha, and the smallest island H with a 63 ha reclamation. The emission level per hectare for each island presumes an average of 135.88 ~ 475.32 tonnes CO_2 with a standard deviation from 85.41 ~ 305.72 tonnes (Table 3).

Although island C has the greatest area, the CO_2 output per ha is less than that of the other islands. The low rate per unit area is due to the low requirement of sand per ha, and the closer distance of the quarry to the site compared with other islands. The material volume of sand for island C is 65,484 m^3/ha while islands F, G, H and I post 131,578, 65,838, 184,126, and 213,110
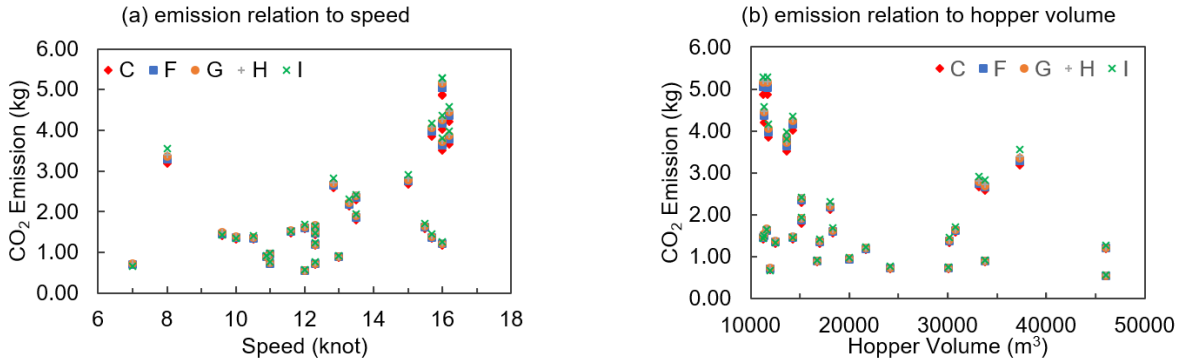
Figure 6. CO_2 Emission per m^3 of material: (a) relation to speed; (b) relation to hopper volume.

m^3/ha respectively (see Appendix Table S4 for different speed-power proportions). Relative emissions are strongly related to sand requirement per ha, distance, and engine power. Islands C and G require similar sand material per ha, but larger emissions characterise the creation of the more distant island G. Island C generates CO_2 of 135 tonnes/ha compared with 144 tonnes/ha from island G (Figure 8). There is a gain in emissions of nine tonnes per ha with increased distance of 5 km, as is apparent from the simulation.
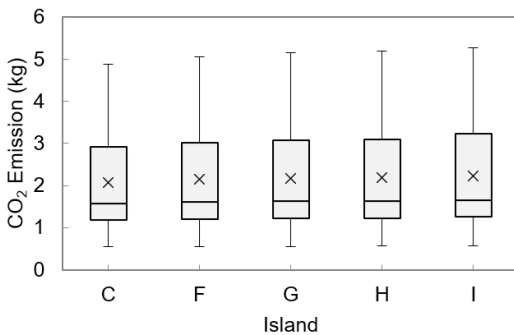
Figure 7. Average CO_2 emission per m^3 of material from different islands.
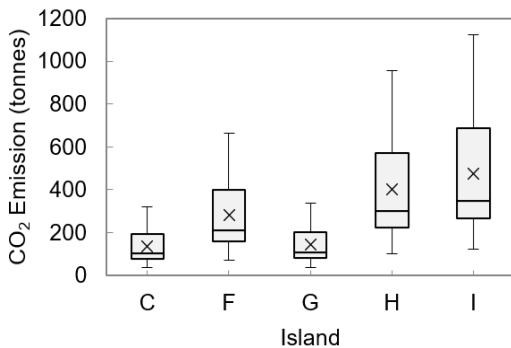
Figure 8. Average CO_2 emission per ha of material from different islands.

4.5. CO₂ Emission from Different Speed-Power Proportions

Emissions generally decline with slower travel, in such cases decreasing from 83% to 68% of the maximum speed (Figure 9a). A rapid decline can be seen below the 80 for 55% speed-power proportion. The 78 for 51% speed-power proportion is a turning point in dredging emissions and duration. Below it, the decrease in emissions corresponds to more prolonged project duration (Figures 9a and 9b). As sailing constitutes the largest proportion of total emissions, the variation from this phase is significant.

By slowing the sailing speed from 83 to 68% of the design speed, the total duration for the creation of island C grows from an average of $12,334 \pm 5,428$ to $14,237 \pm 6,307$ hours, approximately 82 days in overall dredging operations. The standard deviation increases significantly from 226.2 to 262.8 days, more than a one-month gain. The extended duration leads to more equipment utilisation and work hours, raising costs.

5. Conclusion

This study provides a first estimation of emissions from sand mining to supply land reclamation. It set out to demonstrate the emissions of TSHDs exhibiting different speeds, hopper volumes and distance travelled in transporting sand for the Jakarta Bay scheme. Land reclamation, though increasing worldwide, lies beyond the reporting scope of conventional onshore construction emissions, and hence is overlooked in the literature. Given the emergence of new buildings on reclaimed islands, creation of the foundational landmass itself should be accounted for in any inclusive reckoning.

Results provide emission estimation from sand mining activity that can complement the overall shipping or construction data. The utilisation of material from a distant area is now common, with transportation become more frequent. Of the four dredging phases simulated, sailing proposes the largest emissions. It is highly influenced by the distance from quarry to the site, which, in the present Indonesian context, ranges from 47 to 82 km. With a trend to utilise material from distant areas, the proportion of the sailing phase emission is likely to enlarge. Destruction of seagrasses (Unsworth et al., 2018) and mangroves could pose further impacts.

In general, doubling TSHD hopper capacity requires two-thirds more fuel (Bouman et al., 2017), though a larger hopper
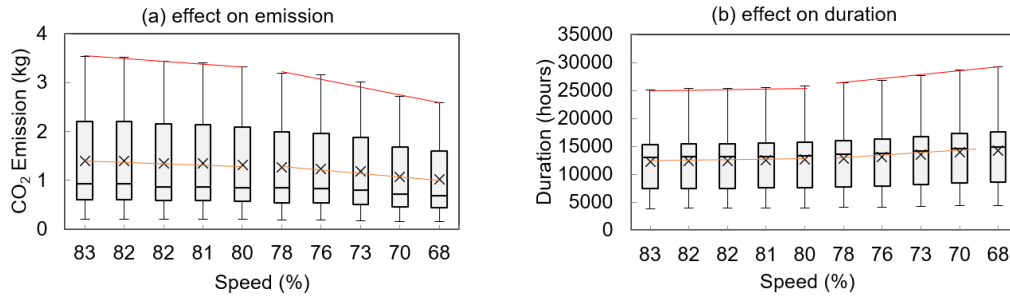
Figure 9. Speed-power proportion effect: (a) on CO_2 emission from sailing phase; (b) on duration.

delivers more efficiency per m^3 material and produces lower emissions. Clearly, a single vessel is insufficient to complete a major land reclamation project: optimising the mix of various dredging assets is critical to minimise emissions.

Regulating the maximum speed to transport material from quarries to the site is essential to emission control. A rapid reduction corresponds with an increase in cycle duration. The result shows the optimum speed-power proportion of TSHDs at 78 for 80% of their design speed. Those speeds utilise engine power from 51 for 55% of the installed diesel capacity. Such simulated information is important in practical operations, but actual emission measurements should be used in real-time accounting and decision making.

Sand for land reclamation is arguably considered as raw material, due to the high energy consumption to shift it from quarry to spoil ground. Although it does not change the shape or function of the material, the extraction, transportation, and deposition stages consume a significant amount of fuel and produce notable levels of emissions. More research into the optimum distance between quarries and reclamation sites is a key to minimising emissions.

Balancing the rapid growth of a new area, through reclamation, while minimising environmental impacts should be subject to extensive carbon accounting. Sustainable land operations recognise emissions and seek to minimise adverse impacts. These issues should be conceived in triple bottom line terms in the planning of new landmass in different jurisdiction.

References

Afiff, M.T., Hutasoit, L., Mujahidin, B., Effendi, A.J., Dewi, K., Irsyad, M., and Roosmini, D. (2013). *Environmental Impact Analysis (EIA) of the G Island Reclamation Plan in the Pantura Reclamation Area of Jakarta*, Jakarta. Jakarta Provincial Environmental Agency. Special Capital Region of Jakarta. Indonesia.

Baolei, Z. (2012). Environmental impacts of sea reclamation in Jiaozhou Gulf, Shandong province of China. *Natural Hazards*, 63(2), 1269-1272. https://doi.org/10.1007/s11069-012-0157-x

Been, K., Bisschop, R., Broos, E., Bijlsma, E., Cloo, H., Cools, J., and Vermeulen, B. (2012). *Hydraulic Fill Manual: For Dredging and Reclamation Works*. Boca Raton, Florida: CRC Press.

Bouman, E.A., Lindstad, E., Rialland, A. I., and Strømman, A.H. (2017). State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping - A review. *Transportation Research Part D: Transport and Environment*, 52, 408-421. https://doi.org/10.1016/j.trd.2017.03.022

Bray, R.N. (1979). *Dredging: A Handbook for Engineers*. London: Edward Arnold.

Castro, B.G., Ooijens, S., and Ingen, L.W.V. (2014). Approaching emissions in dredging. *Terra et Aqua*, 137, 19-26.

Cutroneo, L., Castellano, M., Pieracci, A., Povero, P., Tucci, S., and Capello, M. (2012). The use of a combined monitoring system for following a turbid plume generated by dredging activities in a port. *Journal of Soils and Sediments*, 12(5), 797-809. https://doi.org/10.1007/s11368-012-0486-0

Cuyper, J.B.d., Ansoms, B., and Verboomen, B. (2014). Smart, sustain-able: a life cycle approach to fuel economy as applied to dredging vessels. *Terra et Aqua*, 137, 5-13.

Duan, H., Zhang, H., Huang, Q., Zhang, Y., Hu, M., Niu, Y., and Zhu, J. (2016). Characterization and environmental impact analysis of sea land reclamation activities in China. *Ocean and Coastal Management*, 130, 128-137. https://doi.org/10.1016/j.ocecoaman.2016. 06.006

Ehab Elsayed, G. (2013). *Environmental Balance of Mining from Seafloor*. Ph.D. Technische Universität Bergakademie Freiberg, Freiberg., Germany.

United States Environmental Protection Agency. (1993). Environmental Impact Statement (EIS) for Designation of Deep Water Ocean Dredged Material Disposal Site off San Fransisco, California. https://nepis.epa.gov/Exe/ZyPDF.cgi/94005ZAD.PDF?Dockey=94005ZAD.PDF

United States Environmental Protection Agency. (2020). Nitrogen Oxides Emissions. Report on the Environment. Environmental Protection Agency. https://cfpub.epa.gov/roe/ind icator_pdf.cfm?i=15

Gausel, N.T. (2014). *Optimal Ship Speed and Routing when Considering ECA Regulations*. (Master Thesis). Norwegian University of Science and Technology, Trondheim.

Griggs, G. (2017). *Coasts in Crisis: A Global Challenge*. Oakland: University of California Press.

Guo, H. and Jiao, J.J. (2007). Impact of coastal land reclamation on ground water level and the sea water interface. *Groundwater*, 45(3), 362-367. https://doi.org/10.1111/j.1745-6584.2006.00290.x

Harrison, D.J., Fidgett, S., Scott, P.W., Macfarlane, M., MitchellI, P., Eyre, J.M., and Weeks, J.M. (2005). Sustainable river mining of aggregates in developing countries. *Geological Society*, Special Publication, 250(1), 35-45. https://doi.org/10.1144/GSL.SP.200 5.250.01.05

International Maritime Organization. (2015). Third IMO Greenhouse Gas Study 2014. http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/Third%20Greenhouse%20Gas%20Study/GHG3%20Executive%20Summary%20and%20Report.pdf

Masson-Delmotte, V., Zhai, P., Pörtner, H.O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M., and Waterfield, T. (2018). *Global Warming of 1.5 °C. An IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission path-ways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. Geneva, Intergovernmental Panel on Climate Change. Switzerland

Larson, C. (2018). Asia's hunger for sand takes toll on ecology. *Science*, 39, 964-965. https://doi.org/10.1126/science.359.6379.964

Lu, X.X., Zhang, S.R., Xie, S.P., and Ma, P. K. (2007). Rapid channel incision of the lower Pearl River (China) since the 1990s as a consequence of sediment depletion. *Hydrology and Earth System Sciences*, 11, 1897-1906. https://doi.org/10.5194/hess-11-1897-2007

Mark J. A, P.E. (2008). *A Comparison of Common Dredging Equipment Air Emissions*. (Master Thesis). Michigan Technological University, Houghton.

Nuryati and Faradila, A. (2016). Statistik Pertambangan Bahan Galian Indonesia 2011-2015. The Indonesia Quarrying Statistics. https://www.bps.go.id/publication/download.html?nrbvfeve=YTUwMzI0NWM4ZGEwMTMyOWJmYzk1ZDg4andxzmn=aHR0cHM6Ly93d3cuYnBzLmdvLmlkL3B1YmxpY2F0aW9uLzIwMTYvMTIvMDkvYTUwMzI0NWM4ZGEwMTMyOWJmYzk1ZDg4L3N0YXRpc3Rpay1wZXJ0YW5nYW4tYmFoYW4tZ2FsaWFuLTIwMTEtMjAxNS5odG1sandtwoadfnoarfeauf=MjAyMC0wNi0yMiAyMDoyMzo1Mg%3D%3D

Oberle, B., Bringezu, S., Hatfield-Dodds, S., Hellweg, S., Schandl, H., and Clement, J. (2019). *Global Resources Outlook 2019*. Paris, International Resource Panel. Île-de-France, France

Olmer, N., Comer, B., Roy, B., Mao, X., and Rutherford, D. (2017). Greenhouse Gas Emissions from Global Shipping, 2013-2015. https://theicct.org/sites/default/files/publications/Global-shipping-GHG-emissions-2013-2015_ICCT-Report_17102017_vF.pdf

Ouwerkerk, R., De Jager, A., Kramers, C., and Ooijens, C. (2007). The impact of a decade of intense research on the efficiency of a TSHD. *Proc. of World Dredging Congress*, Lake Buena Vista. FL., USA.

Padmalal, D. and Maya, K. (2014). *Sand Mining: Environmental Impacts and Selected Case Studies*. Dordrecht: Springer. https://doi.org/10.1007/978-94-017-9144-1

Priatna, E., Pranoto, Susanto, D., Mawahib, S. H., Liyantono, Sofyan, S., and Setyaningsih, D. (2014). *Environmental Impact Analysis (Andal) Island Reclamation Plan F*, Jakarta. Jakarta Provincial Environmental Agency. Special Capital Region of Jakarta. Indonesia.

Pronk, J.C. and Lindo, M. (2005). *The Van Oord Projects in Dubai*.

Paper presented at the Coasts and Ports 2005: Coastal Living - Living Coast, Barton, A.C.T. Australia.

Schandl, H., Fischer-Kowalski, M., West, J., Giljum, S., Dittrich, M., Eisenmenger, N., and Fishman, T. (2016a). Global Material Flows and Resource Productivity: Assessment Report for the UNEP International Resource Panel. https://www.resourcepanel.org/sites/default/files/documents/document/media/global_material_flows_full_report_english.pdf

Schandl, H., Fischer-Kowalski, M., West, J., Giljum, S., Dittrich, M., Eisenmenger, N., and Fishman, T. (2016b). Global Material Flows and Resource Productivity: Summary for Policymakers. https://www.resourcepanel.org/file/424/download?token=RMdagO3

Shi, W. (2013). *Dynamics of Energy System Behaviour and Emissions of Trailing Suction Hopper Dredgers*. Ph.D. Technische Universiteit Delft, Delft. Netherlands.

Suo, A., Cao, K., Zhao, J., and Lin, Y. (2015). Study on impacts of sea reclamation on fish community in adjacent waters: A case in Caofeidian, North China. *Journal of Coastal Research*, 73(SI), 183-187. https://doi.org/10.2112/SI73-032.1

Suriadi, I.R., Amsyar, S., Ali, Z., Nurcahyani, Y., Sabur, B., Surjono, H., and Sudrajat, E. (2014). *Environmental Impact Analysis (Andal) Island Reclamation Activity West I*, Jakarta. Jakarta Provincial Environmental Agency. Special Capital Region of Jakarta. Indonesia.

Susanto, K., Simbolon, M., Tjamin, Y. R., Rahmani, U., Iswanto, Jaafar, T., and Tugiyo. (2015). *Environmental Impact Analysis (Andal) Reclamation of H Island*, Jakarta. Jakarta Provincial Environmental Agency. Special Capital Region of Jakarta. Indonesia.

Susanto, K., Tambunan, R.P., Tjamin, Y. R., Santoso, Simbolon, M., Sawarendro, and Iswanto. (2012). *Environmental Impact Analysis (Andal) Kapok Naga Indah Beach Reclamation (Island 2A, 2B, and 1)*, Jakarta. Jakarta Provincial Environmental Agency. Special Capital Region of Jakarta. Indonesia.

Torres, A., Brandt, J., Lear, K., and Liu, J. (2017). A looming tragedy of the sand commons. *Science*, 357(6355), 970-971. https://doi.org/10.1126/science.aao0503

Unsworth, R.K.F., Ambo-Rappe, R., Jones, B.L., La Nafie, Y.A., Irawan, A., Hernawan, U.E., and Cullen-Unsworth, L.C. (2018). Indonesia's globally significant seagrass meadows are under widespread threat. *Science of the Total Environment*, 634, 279-286. https://doi.org/10.1016/j.scitotenv.2018.03.315

U.S. Energy Information Administration. (2015). Marine Fuel Choice for Ocean- Going Vessels within Emissions Control Areas. https://www.eia.gov/analysis/studies/transportation/marinefuel/pdf/marine_fuel.pdf

Wang, K., Zhang, X., Chen, Z., Zhou, F., and Nie, X. (2015). Tidal and prism analysis of sea reclamation project in coastal bay. *Water resources*, 42(5), 635-651. https://doi.org/10.1134/S0097807815050140

Wang, L., Coles, N., Wu, C., and Wu, J. (2014). Effect of long-term reclamation on soil properties on a coastal plain, Southeast China. *Journal of Coastal Research*, 30(4), 661-669. https://doi.org/10.2112/JCOASTRES-D-13-00129.