$^{239/240}$Pu Dispersion Modeling for Emergencies During Nuclear Power Plant Operations in Malaysia

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Abstract

The East Coast of Johor in Malaysia is a strategic area as a candidate site for nuclear power plants.Its location is near coastal area and is therefore convenient to use seawateras a source of cooling for power plants. This makes the East Malaysia waters, and their surroundings stand a high risk of direct radioactive contamination, especially in event of an accident. Pu is a non-conservative or reactive radionuclide that easily settles with particles and has high radiotoxicity and radiochemistry, making it very dangerous. The purpose of this study was to determine the distribution patterns of $^{239/240}$Pu releases in the waters of East Malaysia and the surrounding waters. To determine the affected areas due to $^{239/240}$Pu pollutionusing MIKE flow flexible mesh module and particle tracking module. The magnitude of $^{239/240}$Pu used in this model is based on the disaster in Fukushima Daiichi in 2011. This research canbe used as a mitigation of $^{239/240}$Pu pollution when a nuclear reactor disaster occurs in the area around Indonesia's territorial border. Discharge of $^{239/240}$Pu was simulated during the west and east monsoons season which result in the distribution pattern following the seasonal flow pattern. During the west monsoon, the dispersion speed of $^{239/240}$Pu is four times faster than the east monsoon. The $^{239/240}$Pu distribution is predominantly towards the south, however, the contaminated area was only occurred on the coast of Johor and does not extend to the waters of Indonesia.

Keywords: *Dispersion Model, $^{239/240}$Pu, Hydrodynamic, Particle Tracking, East Coast of Johor*

Introduction

The ratio of ^{239}Pu and ^{240}Pu is often used as a tracer and chronometer in terrestrial and aqueous environments. Sources in the environment come from the results of human activities such as nuclear weapon tests, nuclear bombs, and nuclear accidents such as Nuclear Power Plant (NPP) (Gao *et al*., 2020) and nuclear reprocessing facilities (Peirson *et al*., 1982). Radionuclides discharged into the aquatic environment are also assimilated by living organisms and some of that are passed along the aquatic food chains and may eventually reach humans (IAEA, 2001). ^{239}Pu and ^{240}Pu have a long half-life (^{239}Pu: 2.41 x 10^4 y; ^{240}Pu: 6.56 x 10^3 y) and have high chemical toxicity and radiotoxicity (Perelygin and Chuburkov, 1997).

Nuclear energy is the latest energy solution that is capable of producing electricity with cheap, clean, and environmentally friendly technology (Mudjiono *et al*., 2020). Its existence has now become very important along with the Southeast Asia countries need for their electricity. Malaysia is one of the countries in Southeast Asia that has initiated the construction of a nuclear power plant (NPP). In 2010, the Malaysian government determined candidate sites for nuclear power plants that were located in peninsular Malaysia. There were several candidate locations i.e. Perak, Trengganu, and Johor each with 2 nuclear power plants, while in Kedah there with 1 nuclear power plant (Khusyairi, 2015). Those nuclear power plants were planned located on the coast and Malaysian government has a plan to begin nuclear power plant operations in 2021 (Khusyairi, 2015).

With regard to the operation of a nuclear power plant, is the concern of leaks occurrenceof radioactivity or reactor accidents, either due to human error or natural errors (Periáñez *et al*., 2019). Disposal of hot water waste resulting from cooling process in the nuclear power plant on the coast

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(Mudjiono*et al.*, 2020) could be the way radionuclide waste entered the surrounding waters. The level of distribution may highly dependent on hydrodynamic conditions (Periáñez *et al.*, 2019). Scenarios of the distribution of radionuclide waste from leaks need to be simulated to determine the extent of nuclides that will contaminate the seawater (Prihatiningsih *et al.*, 2020).

The potential for contamination of Indonesian waters by anthropogenic radionuclides is quite high considering that the large number of nuclear power plant development was planned to be operated in Malaysia. The geographical location of the boundaries between Indonesia and Peninsular Malaysia needs special attention, because there may be contamination of radioactive waste around the waters of the outer islands of Indonesia. The Malaysian government has planned to build 2 nuclear power plants on the EastCoast of Johor with a power of 1000 MWe each (Khusyairi, 2015). The purpose of this study was to predict the distribution of $^{239/240}$Pu due to leakage of the BWR-1000 nuclear power plant reactor in the waters of East Johor Malaysia in the west and east monsoons.

Materials and Methods

The study site is located in the coastal area of Johor States, Malaysia, because it is selected as a candidate site for nuclear power plants (Khusyairi, 2015) and the scenario used to release particles for 30 days is according to the Short-Term emergency assessment system of marine environmental radioactivity (STREAMER) at around 8 and 30 days. There are 2 sites selected specifically in the north and south nuclear power plants (Figure 1.).

The main data includes predicted concentration values of $^{239/240}$Pu, predicted tide data developed by DHI (Danish Hydraulic Institute), bathymetry data obtained from demnas (*tanahair.indonesia.go.id/demnas/#/batnas*), and shorelines. While secondary data provide support for primary data in order to obtain model results that are in accordance with the actual situation. Supporting data in the form of wind data downloaded from CMEMS (Copernicus Marine Environment Monitoring Service) and tidal prediction data from theGeospatial Information Agency.

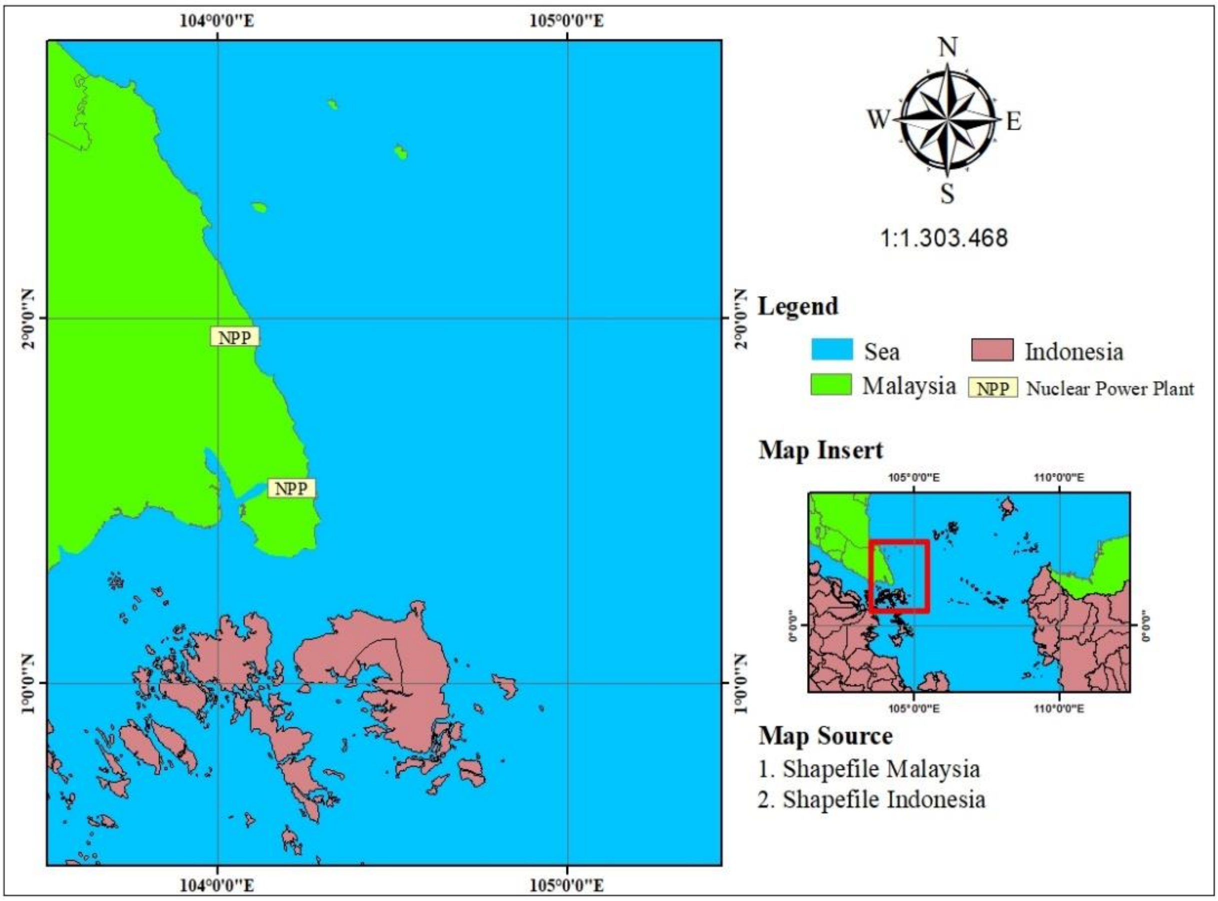


Figure 1. Research Site

This research consisted of two stages, firstly collecting data of wind, bathymetry, tidal, and $^{239/240}$Pu release prediction data in Johor Sea. While the second stage is processing all of the data. The sources $^{239/240}$Pu value in this study is assumed to be the same as the leak that occurred at Fukushima Daiichi in March 2011 with a value 689.92 Bq.m^{-3} every 6 h (Lin *et al*., 2016).

In this study, 2 NPPs were simulated to leak at the same time due to the abort of the emergency reactor cooling system. The leak scenario was made in January which represents the west season and August which represents the east season. This scenario is set for a time of 30 days. The Leak scenario is based on the MIKE flow FM which is governed by the following main equations:

$$\frac{\partial h}{\partial t}+\frac{\partial h\bar{u}}{\partial x}+\frac{\partial h\bar{v}}{\partial y}=hS$$

Note: h = the total water depth; t = the time; x and y = the coordinates; u and v = the velocity components in the x and y; S = the magnitude of the discharge due to point sources. There is also transport equation for scalar quantity:

$$\frac{\partial h\overline{C}}{\partial t}+\frac{\partial h\bar{u}\overline{C}}{\partial x}+\frac{\partial h\bar{v}\overline{C}}{\partial y}=hF_C-hk_p\overline{C}+hC_sS$$

Note: C= the concentration of the scalar quantity; C_s = the concentration of the scalar quantity at the source; S= the magnitude of the discharge due to point sources; K_p= the linear decay rate of the scalar quantity; F_c= the horizontal diffusion term defined by:

$$F_C=\left[\frac{\partial}{\partial x}\left(D_h\frac{\partial}{\partial x}\right)+\frac{\partial}{\partial y}\left(D_h\frac{\partial}{\partial y}\right)\right]C$$

Note: D_h= the horizontal diffusion coefficient, this study uses two horizontal dispersion coefficients with values of 47.99 m^2.s^{-1} during the west monsoon and 11.33 m^2.s^{-1} during the east monsoon (Xu and Chua, 2017).

Result and Discussion

Surface current simulation

Current conditions at low tide in the west monsoon (Figure 2a.) have a dominant direction to the northwest and move towards the coast. Surface current speeds range from 0.1 to 0.9 m.m^{-1}, the current speed around the coast is faster than in the open sea. Current conditions during the highest tide in the west monsoon (Figure 2b.) have a dominant direction to the northeast and the current moves away from the coast. Surface current speeds range from 0.2 m.s^{-1} to 1.8 m.s^{-1}. Current conditions at low tide in the east monsoon (Figure 2c.) have a dominant direction to the northwest and the current moves closer to the shore. Surface current velocity ranges from 0.15 to 1.35 m.s^{-1}. The current speed in the north is faster than in the south. Surface current conditions during the highest tide in the east monsoon (Figure 2d.) have a dominant direction to the east and the current moves away from the coast. Surface current velocity ranges from 0.08 m.s^{-1} to 1.12 m.s^{-1}. The current speed in the north is faster than in the south.

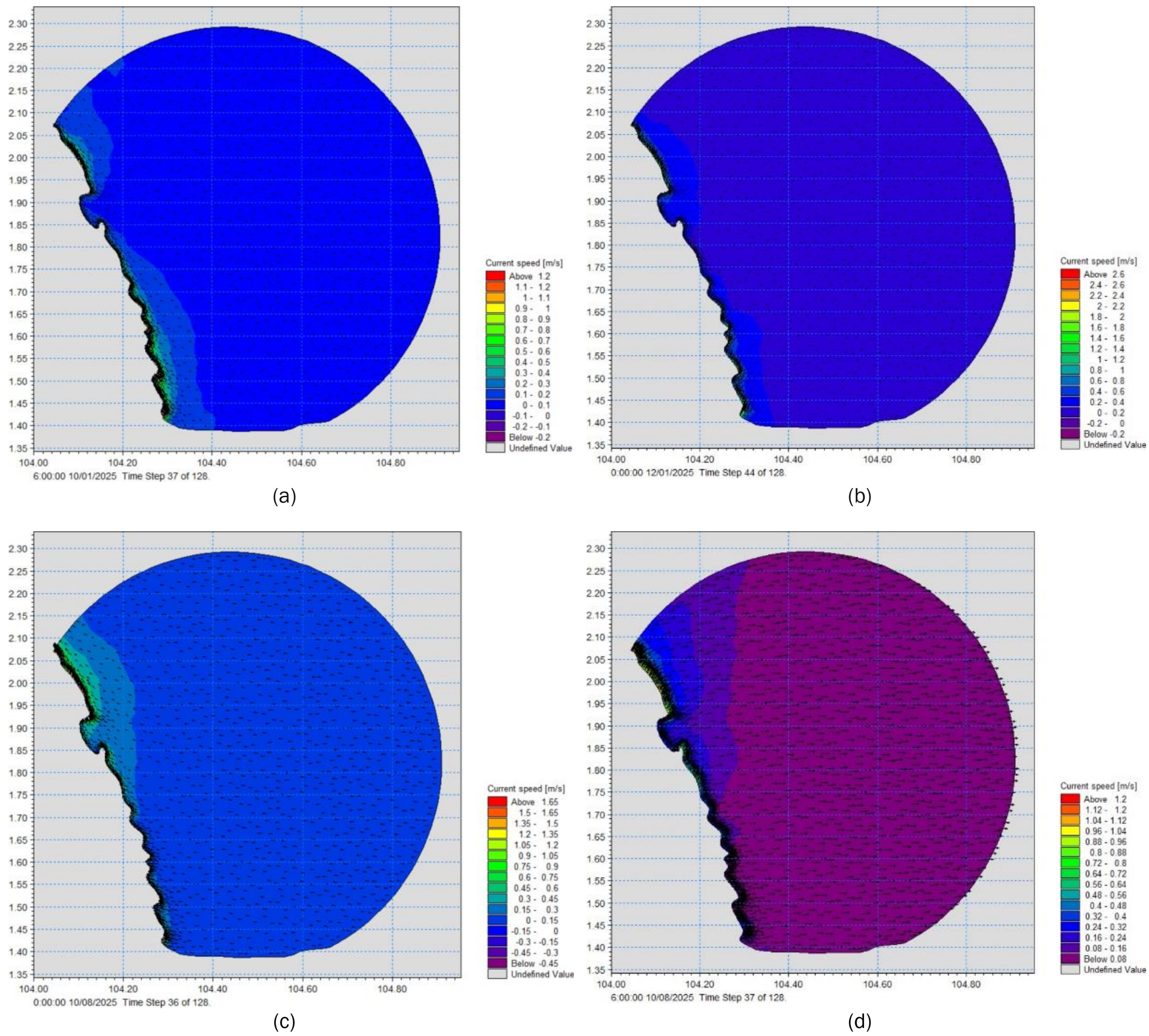
Dispersion model of $^{239/240}$Pu

Figure 3 and 4 show the distribution of radionuclides $^{239/240}$Pu from the first to the fourth week, the distribution direction is more inclined to the south, which shows the highest concentration values at the release point of around 3708.4 Bq.m^{-3} and the outermost average concentration was 150 Bq.m^{-3}. Based on the Regulation of the Head of the Nuclear Energy Supervisory Agency Number (BAPETEN) 7 of 2017 concerning changes to the Regulation of the Head of the Nuclear Energy Supervisory Agency Number 7 of 2013 concerning Limits of Environmental Radioactivity Values, the quality standard of radioactivity in water bodies is 2600 Bq.m^{-3} so that in this research scenario the concentration of Pu in water bodies adjacent to the leak point exceeds the highest permissible limit value. Also, according to the Regulation of Atomic Energy Licensing Board of Malaysia concerning Radioactive Waste Management Regulations the values of $^{239/240}$Pu in residual form must be approximately 1000 Bq.m^{-3} (AELB. 2011). However, if Pu migrates to Indonesian territory, it must be below the standard level of radioactivity because it can be harmful to the marine environment. The movement of the $^{239/240}$Pudistribution seems to have decreased in concentration, due to the process of advection and diffusion (Muslim *et al*., 2017). In this study, it can be seen that at high tide, surface water moves away from the beach and at low tide, it approached the coast. According to Rampengan (2009) the surface currents at high tide will carry a massof water from the coast to the open sea, while at low tide it will fill the void on the beach so that current moves closer to it.

The distribution of the $^{239/240}$Pu particles on the surface of waters is affected by the current. Surface currents are generated by seasonal winds. In this study, the west and east monsoons were applied. The particle distribution area of $^{239/240}$Pu duringthe west and east monsoons is different because the current dispersion ability in the east monsoon is not as strong as the west monsoon. In accordance with Xu and Chua (2017) that the coefficient of horizontal dispersion during the west monsoon was 47.99 $m^2.s^{-1}$ and the east monsoon was 11.33 $m^2.s^{-1}$, it meant that the $^{239/240}Pu$ ability dispersion during the west monsoon will be four times faster than the east monsoon. The pattern of current movement in this study is also influenced by tides so that the current moves away from and near the coast periodically.

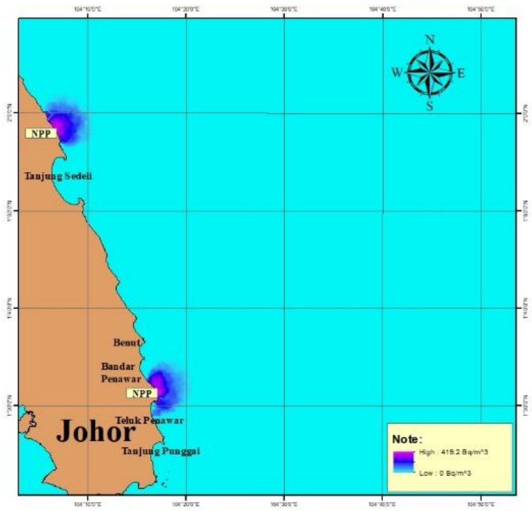
The scenario is that a reactor leak occurred in early January 2025, where the release of $^{239/240}Pu$ in the water was seen as far as 7.64 km (Figure 3a.). Because of the reactor leakage continuously releasing $^{239/240}Pu$, there was an increase in the contamination radius within 15.48 km in the first week (Figure 3b.). When the dispersion of $^{239/240}Pu$ in the waters is carried by currents parallel to the coast and moves to the south and partly to the north, the currents moving south meets Tanjung Punggai which prevent the distribution of $^{239/240}Pu$ as a result, $^{239/240}Pu$ can't reach to the area. This process occurs during the second and third weeks, the farthest radius of $^{239/240}Pu$ was only 13.8 km (Figure 3c and 3d). The distribution of $^{239/240}Pu$ in the second and third weeks was not as far as that of the first week. This is because the current heading south is not strong enough to carry $^{239/240}Pu$, besides that,$^{239/240}Pu$ has non-conservative or reactive properties, so it easily settles to the bottom ofthe water (Yamada and Zheng, 2020).

In the fourth week, the contamination area of $^{239/240}Pu$ around the northern nuclear power plant was 78.04 km^2 and that of the southern nuclear power plant was 139.15 km^2 (Figure 3e.). The northern nuclear power plant has a dispersion pattern that leads to the sea ina semicircular shape, meaning that there is no barrier for $^{239/240}Pu$ to spread out into the water. In contrast, the southern

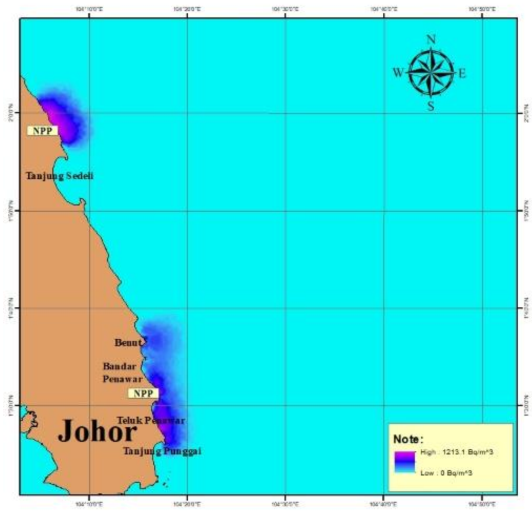


(a) (b) (c) (d)

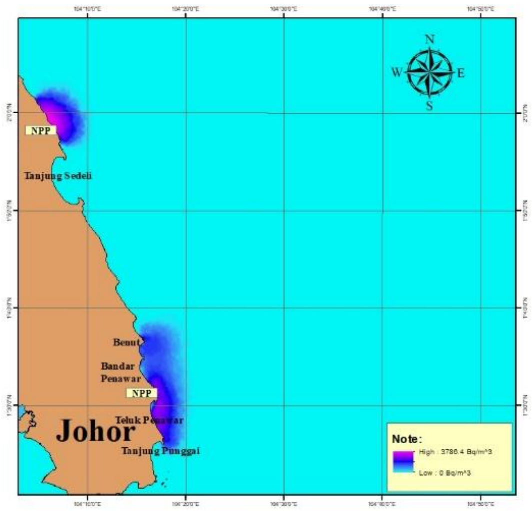
Figure 2. Current pattern: (a) low tide (b) high tide at west monsoon and (c) low tide (d) high tide at east monsoon.



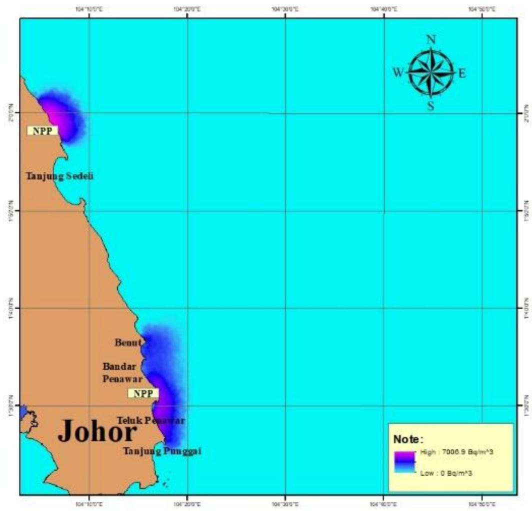
(a)



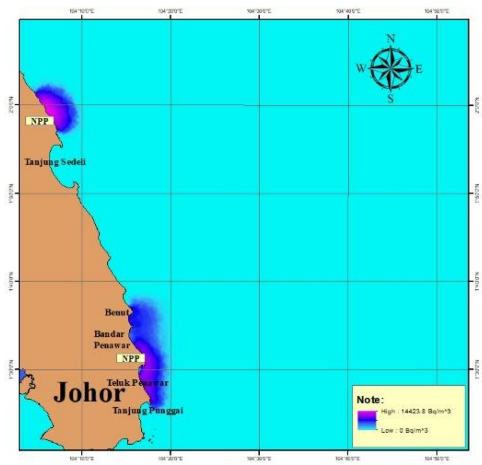
(b)



(c)



(d)



(e)

Figure 3. Dispersion of $^{239/240}Pu$ in the west monsoon: (a) on the first day, (b) first week (c) second week, (d) third week and (e) fourth week. Note: = Land; = Sea

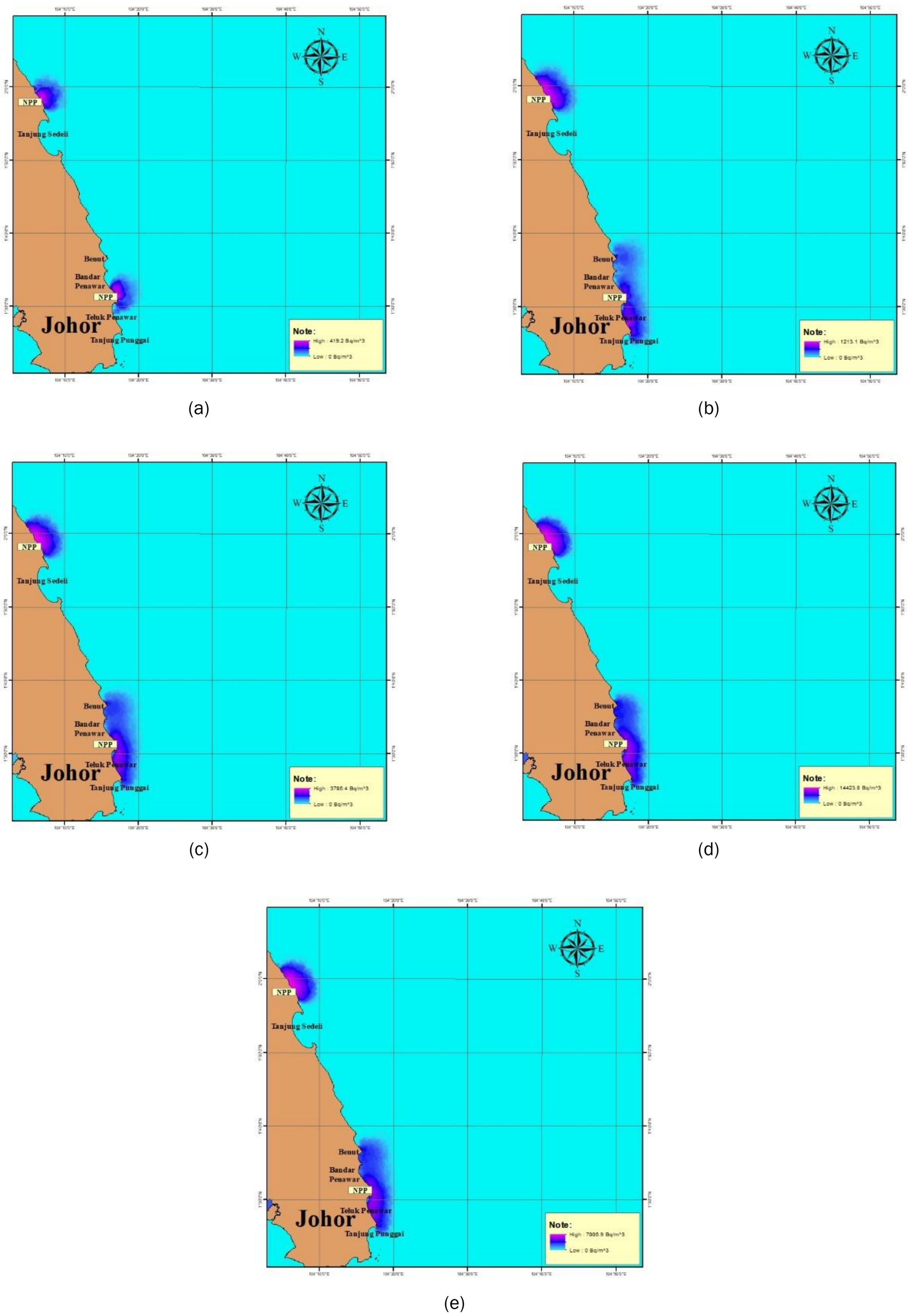


Figure 4. Dispersion of $^{239/240}$Pu in the east monsoon: (a) on the first day, (b) first week (c) second week, (d) third week and (e) fourth week. Note: [land symbol] = Land; [sea symbol] = Sea

nuclear power plant has a dynamic beach shape with the characteristics of a headland (Tanjung Punggai) and a bay (Teluk Penawar) that can prevent the spread of $^{239/240}$Pu.

During the east monsoon in early August, the $^{239/240}$Pu release was only 5.24 km (Figure 4a.) not as far as during the west monsoon. The horizontal dispersion ability of the east monsoonis not as strong as twest monsoon, this is in accordance with Xu and Chua (2017) research result that during east monsoon the wind is weaker. In the first week, the farthest radius for $^{239/240}$Pu dispersion is up to 8.76 km (Figure 4b.) which is dominantly directed to the south.There is Penawar Bay located in the southern part of the nuclear power plant which causes $^{239/240}$Pu to be trapped and make it difficult to spread away from the coast. During the second and third weeks, reactor leaks at the two nuclear power plants continued to occur as a result the distribution of $^{239/240}$Pu was further, up to ±12 km (Figure 4c, 4d.). This happened becauseas the current leads to the east, the $^{239/240}$Pu particles that are trapped in Teluk Penawar come out and slightly pass-through Tanjung Punggai. The dispersion area of $^{239/240}$Pu in the last week (Figure 4e.) in the southern nuclear power plant reached 101.1 km^2 while in the northern nuclear power plant it was only 43.84 km^2. Based on Figure 3 and 4, the activity of $^{239/240}$Pu tends to be higher in shallow waters and lesser in deep waters. The concentration of $^{239/240}$Puis higher in the depth of 0-10 m, this statement is reinforced by the research of Widiyanto *et al.*, (2014).

The $^{239/240}$Pu dispersion is predominantly towards the south. During the west monsoon, the distribution is wider than in the east monsoon but the concentration value was higher during the east monsoon (Figure 3, 4.). The current direction in Johor waters is occasionally away from the coast. However, $^{239/240}$Pu particles are reactive in nature and cannot be widely dispersed on the high seas. Particles$^{239/240}$Pu have the property of being easy to settle and are affiliated with floating objects in the waters, so their distribution pattern is only around the coast(Periáñez *et al*., 2019). When the current moves away from the coast, the particles are dispersedaway from the output point towards the open sea, but because the currents are also driven by the tides, occasionally the current direction approaches the coast which caused the dispersion of the particles tobe stuck in the shallow sea. From the two NPP that experienced leakage simultaneously, it was found that the distribution of $^{239/240}$Pu was not too far and did not even reach the territory of Indonesia because the current velocity was weak, i.e. 1.8 m.s^{-1}. According to Daruwedho *et al*. (2016) the weak current is moving at a speedof 0-4 m.s^{-1}, therefore it is unable to carry reactive (non-conservative) particles to spread to offshore.

Conclusion

According to modelling of the release of $^{239/240}$Pu due to leakage of the BWR-1000 type reactor in both nuclear power plants in coastal area of Johor States, Malaysia concluded that the maximum contaminated area after 1 month will reach 139.15 km^2 and the outermost average concentration is 150 Bq/m^3, and will not reach Indonesian territory due to weak currents and $^{239/240}$Pu has reactive particles.

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