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Full Paper

Naturally occurring radioactive materials in sea water and beach sand near Map Ta Phut Industrial Estate, Thailand

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Abstract: Naturally occurring radioactive materials were assessed in sand and sea water along the coastline to the east of Map Ta Phut Industrial Estate, the largest petrochemical base in Thailand. Concentrations of ^{226}Ra, ^{232}Th and ^{40}K activities in sand and sea-water samples collected from Pradu Bay were measured using a gamma-ray spectrometer, while radon gas (^{222}Rn) concentration in sea-water samples was measured using a RAD7 portable radon detector complete with a set of RAD7-H_2O accessories. Radiation hazard indices such as radium equilibrium (Ra_{eq}), absorbed outdoor external dose rate (D_{out}) and annual outdoor effective dose rate (E_{out}) were estimated to evaluate radiation risks for humans and the environment along the coastline to the east of the Industrial Estate. Results indicate lower radioactive concentrations of ^{226}Ra, ^{232}Th, ^{40}K and ^{222}Rn in sea-water samples than the recommended values in drinking water. Most sand samples contain lower ^{226}Ra, ^{232}Th and ^{40}K activity concentrations than the guideline, while the values of E_{out} in sand samples are below the recommended limit.

Keywords: naturally occurring radioactive materials, Map Ta Phut Industrial Estate, Thailand

INTRODUCTION

Naturally occurring radioactive materials (NORMs) result from the decay of uranium-238 (^{238}U) and thorium-232 (^{232}Th), which releases radium-226 (^{226}Ra), radon-222 (^{222}Rn) and potassium-40 (^{40}K) [1]. The main radionuclides in NORMs are long-lived and the primary external sources of human body irradiation. Exposure to NORMs can result in adverse health consequences [2, 3]. ^{222}Rn as a radioactive inert gas decaying from ^{226}Ra is dangerous when inhaled or ingested,

introducing lead and polonium daughter isotopes into the lung membranes [3]. International scientific organisations have concluded that radon can cause lung cancer in humans when breathing radon entering the air from the soil beneath homes and household water [3, 4]. Drinking water containing radon can cause stomach cancer [4]. The US Environmental Protection Agency has set a maximum contaminant level for radon in drinking water at 11.1 becquerel/litre (Bq/l) [5], while the European Commission suggests a concentration reference level of 100 Bq/l for radon in drinking water. If the activity is higher than 1000 Bq/l, then remedial measures should be taken [6].

Recently, it was recognised that the NORMs present in various industrial processes and industries such as mining, metal extraction, water treatment, phosphates, fertilisers and hydrocarbons can cause unsafe radiation doses to workers, resulting in both public and environmental contamination [4]. NORMs level monitoring in industrial areas is therefore required to control radiological hazards. In Thailand Map Ta Phut (MTP) industrial complex was developed during 1989 in the middle of Rayong Bay in eastern Thailand as the largest petrochemical industrial complex in the country [7-9]. Besides petrochemical plants, this industrial area contains more than 150 factories including fertiliser factories, oil refineries and coal-fired power stations, triggering severe air and water pollution [10]. The MTP complex is one of the most toxic hotspots in the country, causing pollution-related health impacts such as cancer and birth deformities [11, 12]. It was reported that volatile organic compounds such as benzene, vinyl chloride and chloroform were released by some industries in the MTP industrial zone at levels 60-3000 times higher than the safety standards [12-14]. Severe degradation of the coastal environment including coastal erosion, air and soil pollution and water quality in MTP areas has been continuously reported [9, 13, 15, 16].

Several MTP industries involving NORMs are located in the coastal zone of Rayong Bay, surrounded by popular tourist attractions such as Suchada and Sai Thong beaches and the important aquacultural farming area of Pradu Bay [15]. To prevent the radiological threat to the public and coastal communities, evaluating the NORMs exposure situation in these areas is urgently required. The objectives of this study are therefore to report the natural radioactivity concentration and assess the radiological risk from exposure to radioactive sea water and beach sand along the Suchada and Sai Thong beaches. The results from this study can be used to set up a proper policing policy to control industrial-waste pollution and manage radioactive residues generated by the MTP industrial complex.

MATERIALS AND METHODS

Study Area

The study area was the coastal zone of the MTP Industrial Estate, shown in Figure 1, comprising Pradu Bay and Suchada and Sai Thong beaches between latitudes 12.66°-12.68°N and longitudes 101.15°-101.22°E. Geologically, the study area is characterised by recent terrace deposits, while the beach materials are primarily composed of fine to medium sand with the median size (d_{50}) of 0.1-0.6 mm [17]. Climate and sea conditions are dominated by the south-west monsoon (May-September) and north-east monsoon (December-March). The predominant wave height is less than 1 m with a wave period of 5-6 seconds [18]. The tides along the bay are diurnal and semi-diurnal depending on lunar age, with a maximum tidal current speed of 0.3-0.5 m/s and direction mainly west-north-west to east-south-east [18].

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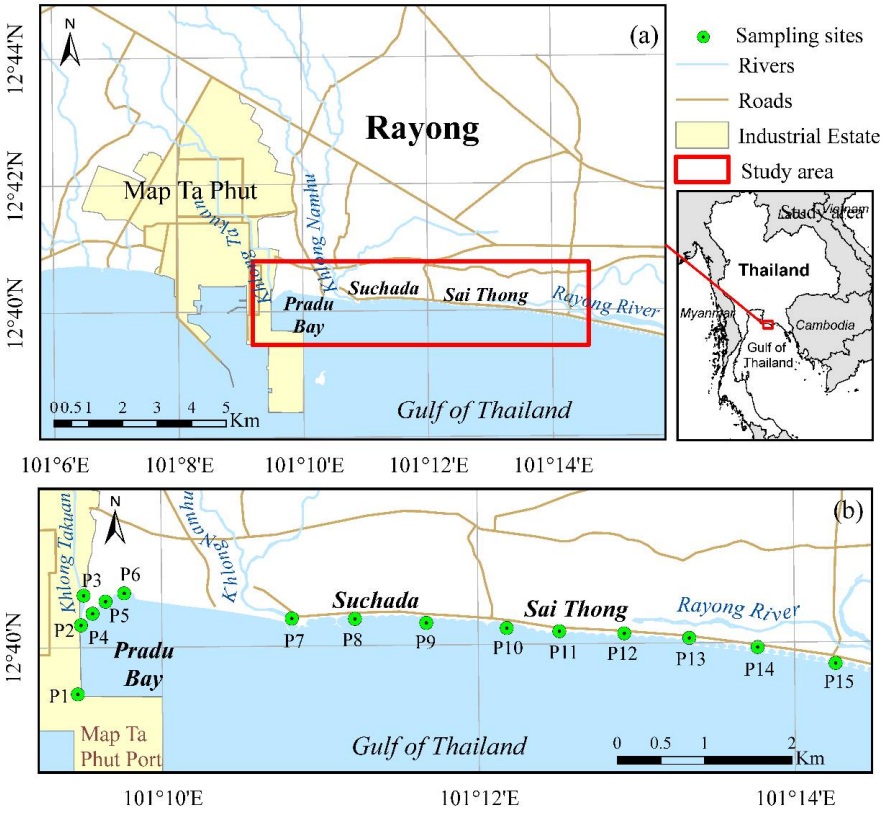

Figure 1. MTP Industrial Estate: a) study area; b) locations of water and sediment sampling

In 1981 the Eastern Seaboard project was developed following implementation of the Fifth Five-Year National Economic and Social Development Plan to accelerate the region's urban-industrial development [18]. The MTP district was selected as a major base for an industrial port complex containing petrochemical, fertiliser and soda ash industries. The Industrial Estate Authority of Thailand and the MTP project executing agency constructed the MTP port and estate development (Figure 1a) in 1989 to promote heavy chemical and petrochemical industries. After the MTP port was completed in the centre of Rayong Bay, the coastline to the east of the MTP port covering Pradu Bay and Suchada and Sai Thong beaches (Figure 1), all well-known tourist attractions, experienced negative environmental impacts [9, 13]. Marine black sediment (35 cm thick) composed of petroleum hydrocarbons (0-170 mg/kg dry weight) and mercury (0.15-1.61 mg/kg dry weight) appeared [15]. Recently, hundreds of dead fish were washed up along Pradu Bay. The wastewater draining from factories via Klong Ta Kuan (Figure 1) was believed to be the main cause of the fish deaths [16, 19]. This pollution issue remains a primary concern for both local communities and tourists in this area.

Sample Collection and Preparation

To assess the natural level of environmental radioactive materials in the study area, sea-water and beach sand samples were collected at 15 locations (P1-P15) (Figure 1b) in February 13-14, 2019. Four 250-mL samples of sea water were collected at each sampling site. Glass vials were used to measure radon levels by RAD-H_2O (an accessory to RAD7), an *in situ* radon measuring device (Figure 2a). Radon content in the sea-water samples was measured immediately in the field after sample collection. Five litres of sea water were also collected in plastic gallon containers for

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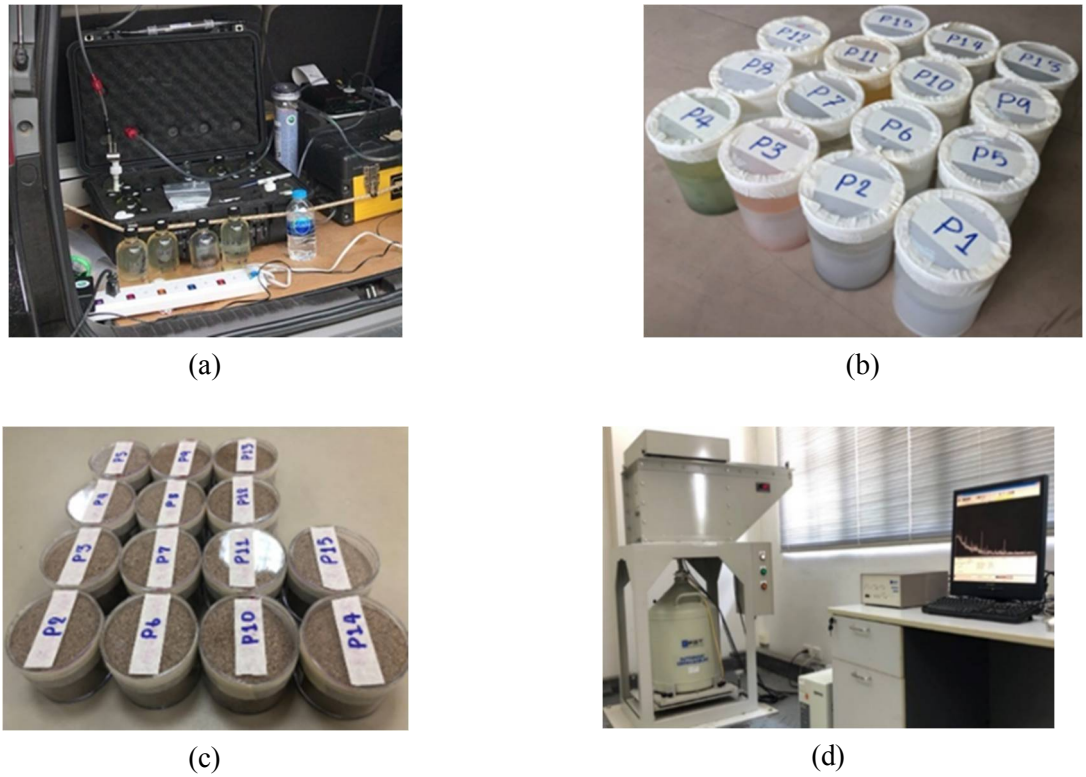
measurement of radionuclides in the water using gamma spectrometry. Sand samples of 1 kg each were also collected at the 14 sampling sites (P2-P15), sifted out from the rubble and oven-dried for 24 hr at 105°C. The sea-water samples and dried sand samples were packed in 1-kg polyethylene Marinelli beakers and cylindrical plastic containers. The containers were sealed with silicone glue and PVC tape, weighed and analysed at the NORMs and Radon Laboratory, Thailand Institute of Nuclear Technology (Public Organisation). The sea-water samples, beach sand samples and gamma-ray detector used in this study are shown in Figures 2 b-d.



(a) (b)

(c) (d)

Figure 2. Radioactivity measurement: a) set-up of RAD-H_2O accessories; b) sea-water samples; c) beach sand samples; d) gamma-ray detector

Radon Measurement and Annual Effective Dose Calculation

Dissolved radon (^{222}Rn) in the sea-water samples was measured using a commercial radon-in-air monitor (RAD7, Durridge Co., USA) with an attachment known as RAD-H_2O, which enables radon measurement in water over the range of 0.37-14800 Bq/l. The measurements were performed using WAT250 protocol [20] for 30 min. per sample. The sample bottles were connected to the RAD7 whose internal air pump was used to re-circulate a closed air loop through the water samples to purge radon from the water into the air loop. The air was continuously recirculated through the water to extract radon until the RAD-H_2O system reached equilibrium (within 5 min.) and no more radon was separated from the water sample. The RAD7 counted the alpha-decaying radon polonium progenies ^{218}Po and ^{214}Po as a measurement of ^{222}Rn concentration. These automated systems are described by Burnett et al. [21] and Dulaiova et al. [22]. Radon concentration in the water samples was reported in Bq/l. The sensitivity of the detectors was 0.0136 count/min./Bq/l. The total annual effective dose due to exposed radon concentration in sea water by inhalation for local people and tourists in the study area was calculated using Eq.1 [23]:

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$$E_{Rn} = C_{RnW} \times R_{aW} \times F \times O \times DCF \quad (1)$$

where E_{Rn} is the effective dose from inhalation of radon gas (millisievert/year), C_{RnW} is the radon concentration in water (kBq/m^3), R_{aW} is the ratio of radon in air to radon in tap water (10^{-4}), F is the equilibrium factor between Rn and its decay products (0.6), O is the average outdoor occupancy time per person (1760 h/y) and DCF is the dose conversion factor for radon exposure (9 mSv/hr per Bq/m^3).

NORMs Measurement in Sea Water and Beach Sand Samples

In this study the ^{226}Ra, ^{232}Th and ^{40}K radionuclides in the sea-water and sand samples were analysed using a high-purity germanium detector (model no. IGC30185, Princeton Gamma-Tech, USA) with a relative efficiency of 30%. The energy resolution (full width at half maximum) of the detector was 2 keV at 1332 KeV of a 60°C source. Energy and detector efficiency calibrations were carried out using certified reference materials IAEA-RGU-1 and IAEA-RGTh-1 to analyse the sand samples, while certified reference materials (GT stem 3000, Eckert & Ziegler, ISOTOPE multinuclide) were used to analyse the sea-water samples.

Each sample was placed on the gamma-ray detector and was counted for 24 hr. Background intensities were obtained from counting blank cylindrical plastic containers and blank Marinelli beakers under the same conditions before measuring the samples. Activities of ^{226}Ra, ^{232}Th and ^{40}K in the sea-water and sand samples were determined via the 186-keV, 911-keV and 1460-keV photopeaks respectively. In this study ^{232}Th in the sea-water samples was determined from the 238.6 keV of ^{212}Pb because the peak of ^{232}Th was not found at 911 keV. The average value of the background counts was subtracted from the sample counts. Then the activity concentration (C) in the sea-water samples (Bq/l) and sand samples (Bq/kg) was calculated using Eq. 2, following Dabayneh et al. [23]:

$$C = \frac{C_a}{\varepsilon \times I_{eff} \times M_s} \quad (2)$$

where C_a is the net gamma count rate (count/sec.), ε is the detector efficiency of a specific γ-ray, I_{eff} is the intensity of the γ-line in radionuclides and M_s is the mass or volume of the sample in kg or litre.

Radiological Risk Health Assessment

The United Nations Scientific Committee on the Effect of Atomic Radiation (UNSCEAR) [3] and the International Commission on Radiological Protection (ICRP) [24] defined various risk parameters that should be considered when analysing radiological risks on human health in the environment. The assessment of radiological health risk is based on the expected exposure in terms of time and concentration [25]. One of the typical radiation risk indices is the absorbed outdoor external dose rate (D_{out}) due to the mean activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K at 1 m from ground level. The D_{out} (nGy/hr) in each sample can be obtained from Eq. 3 [26]:

$$D_{out} = 0.429A_{Ra} + 0.666A_{Th} + 0.0417A_K \quad (3)$$

where A_{Ra}, $A_{Th}$and A_K are the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in Bq/kg respectively. The ICRP [24] recommends a total annual outdoor effective dose rate (E_{out}) limit of less than 1 mSv/y. E_{out} in mSv/y can be determined from Eq. 4 [3]:

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$$E_{out} = D_{out} \times 8760 \times 0.7 \times 0.2 \times 10^{-6} \quad (4)$$

where D_{out} is the absorbed outdoor external dose rate in air (nGy/hr), 8760 is the number of hours in one year, 0.7 is the conversion factor (for adults), which covers the absorbed dose rate in air to human effective dose (mSv/Gy) of terrestrial gamma ray and 0.2 is the outdoor occupancy factor.

The radium equivalent activity (Ra_{eq}) is another common index for assessing radiation hazards [27]. The Ra_{eq} index can be applied when ^{226}Ra, ^{232}Th and their progenies are in radioactive equilibrium. Beretka and Mathew [28] calculated the Ra_{eq} (Bq/kg) using Eq. 5:

$$Ra_{eq} = A_{Ra} + 1.43A_{Th} + 0.07A_K \quad (5)$$

where A_{Ra}, A_{Th} and A_K are the activity concentrations in Bq/kg of ^{226}Ra, ^{232}Th and ^{40}K respectively. The UNSCEAR [3] suggested that Ra_{eq} should be less than 370 Bq/kg.

RESULTS AND DISCUSSION

Activity Concentrations of NORMs and Radon in Sea Water

The measured activity concentrations (C) of ^{226}Ra, ^{232}Th and ^{40}K in 15 sea-water samples are reported in Table 1. Radionuclide analyses of the samples indicate that the activity concentration of ^{226}Ra along Pradu Bay to Sai Thong beach varies in a narrow range between 4.05±0.01-12.70±0.02 Bq/l, with an average concentration of 8.33±0.12 Bq/l. The maximum concentration of 12.70±0.02 Bq/l is found near the mid-coastline between the MTP port and Rayong River mouth. Water samples collected from Pradu Bay (P1-P6), which receives water from the major MTP drainage channel, Klong Takuan (Figure 1), contain ^{226}Ra activity concentrations at a similar range as found in sea water collected along Suchada and Sai Thong beaches. However, the concentration of ^{226}Ra found in the study area is remarkably higher than that reported for the Mediterranean Sea ($<2\times10^{-4}$ Bq/l) [29]. Concentrations of ^{232}Th activity found along the study area are mostly less than 0.05 Bq/l (below the detection limit of the detector), with similar ranges as found in Egypt, Sudan and Ghana [30]. Higher ^{232}Th concentrations ranging between 0.19-0.29 Bq/l are found in several locations along the study area (P5, P6, P9 and P11), although they are lower than those observed in Yemen (0.3-2.93 Bq/l) and Nigeria (12 Bq/l) [30].

Table 1 also shows ^{40}K activity concentrations ranging between 4.65±0.01-15.27±0.02 Bq/l. Values for sea-water samples collected offshore (P1) and near the MTP drainage channel (P2, P3 and P7) are below 6 Bq/l and lower than values reported for the world oceans (12 Bq/l) [29]. By contrast, sea-water ^{40}K concentration along the sandy beaches varies between 13-15 Bq/l, which is comparable to sea-water values for the coastal zones of Egypt (13.8-17.56 Bq/l) [29] but lower than that of the Arabian Gulf (18.6-19.1 Bq/l) [31]. The higher concentration of ^{40}K is possibly caused by water draining from Klong Namhu channel located upcoast of the beaches (Figure 1).

The result of ^{222}Rn gas analysis in Table 1 reveals that radon concentrations in sea water along the study area range from ~0 to 1.11±0.06 Bq/l, which is significantly below the recommended values for drinking water (Table 2). Sea water sampled near Klong Takuan drainage channel (P2-P6) contains very low ^{222}Rn concentration compared to samples collected along Suchada and Sai Thong beaches. This result implies that industrial activities in the MTP Industrial Estate may not increase radiological harm to the adjacent coastal environment. The estimated annual effective dose due to exposure of radon concentration in sea water is also presented in Table 1 and ranges from ~0 to 0.4186 mSv/y, which is lower than the dose limit of 1 mSv/y [24]. Tourists

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Table 1. Activity concentration of ^{226}Ra, ^{232}Th, ^{40}K and ^{222}Rn in sea-water samples collected from Suchada beach, Sai Thong beach and Pradu Bay and estimated total annual outdoor effective dose rate (E_{out}) at each sampling site

Sample no.	Specific activity (Bq/l)			^{222}Rn (Bq/L)	E_{out} (mSv/y)
	^{226}Ra	^{232}Th	^{40}K		
P1	4.05±0.01	< LLD (0.05 Bq/l)	5.62±0.01	< LLD (0.37 Bq/l)	~0
P2	7.24±0.01	< LLD (0.05 Bq/l)	4.97±0.01	< LLD (0.37 Bq/l)	~0
P3	8.12±0.01	< LLD (0.05 Bq/l)	4.65±0.01	< LLD (0.37 Bq/l)	~0
P4	7.96±0.01	< LLD (0.05 Bq/l)	12.44±0.02	< LLD (0.37 Bq/l)	~0
P5	10.98±0.02	0.37±0.0006	11.79±0.02	< LLD (0.37 Bq/l)	~0
P6	10.48±0.02	0.19±0.0003	12.20±0.02	< LLD (0.37 Bq/l)	~0
P7	11.64±0.02	< LLD (0.05 Bq/l)	5.64±0.01	< LLD (0.37 Bq/l)	~0
P8	4.96±0.01	< LLD (0.05 Bq/l)	13.00±0.02	< LLD (0.37 Bq/l)	~0
P9	7.01±0.01	0.29±0.0004	13.83±0.02	1.11±0.06	0.4186
P10	7.50±0.01	< LLD (0.05 Bq/l)	15.07±0.02	0.93±0.05	0.3507
P11	7.82±0.12	0.32±0.0005	14.40±0.02	< LLD (0.37 Bq/l)	~0
P12	12.70±0.02	< LLD (0.05 Bq/l)	14.22±0.02	0.85±0.04	0.3205
P13	8.07±0.01	< LLD (0.05 Bq/l)	15.27±0.02	0.64±0.03	0.2414
P14	9.86±0.01	< LLD (0.05 Bq/l)	14.82±0.02	0.86±0.04	0.3243
P15	6.52±0.01	< LLD (0.05 Bq/l)	15.25±0.02	1.08±0.05	0.4073
Av.	8.33±0.12	0.29±0.0004	11.54±0.02	0.82±0.04	0.3438
Max.	12.70±0.02	0.37±0.0006	15.27±0.02	1.11±0.06	0.4186
Min.	4.05±0.01	0.19±0.0003	4.65±0.01	0.64±0.03	0.2414
S.D.	2.41	0.08	4.10	0.28	0.0650

Note: LLD is the lowest limit of detection.

Table 2. International radon guidance and parametric values in drinking water

Directive/recommendation	Activity concentration (Bq/l)	Reference
EURATOM Drinking Water Directive	100-1000 [a]	EURATOM, 2013 [32]
24 EU Member States [b]	100	EURATOM, 2013 [32]
Ireland, Portugal, Spain	500	EURATOM, 2013 [32]
Finland	1000	EURATOM, 2013 [32]
WHO guidance level	100	WHO, 2008 [33]
US-EPA maximum contaminant level	11.1	US-EPA, 1999 [5]
US-EPA alternative higher maximum contaminant level	148	US-EPA, 1999 [5]

Note: [a] For values >1000 Bq/l, remedial action without further consideration is justified in all EU countries.
[b] Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, France, Germany, Greece, Hungary, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Romania, Slovenia, Sweden, United Kingdom

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and aquaculturists who typically spend less than 10 hr a day and not all year in this coastal zone would therefore not be harmed by inhaling ^{222}Rn contained in sea water.

Activity Concentrations of NORMs and Radon in Beach Sand

The activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in sand taken along Pradu Bay to Sai Thong beach (P2 to P15 in Figure 1) are shown in Table 3. The estimated hazard indices (D_{out}, E_{out} and Ra_{eq}) for each sand sample are also reported. ^{226}Ra activity concentration in the sand samples varies between 33.98±0.05-285.93±0.43 Bq/kg, with an average value of 95.53±0.14 Bq/kg. Based on the international guidance and parametric values of NORMs in sediment (Table 4), most of the sand samples taken near Klong Takuan (P5) along Pradu Bay (P2-P3), the fishery and aquacultural community (Figure 3a), have ^{226}Ra activity concentrations 3 times higher than the global average value, while ^{226}Ra concentrations in sand samples taken along Suchada and Sai Thong beaches vary between 0.85-1.80 times the global average value, except for P15 with the maximum ^{226}Ra concentration of 286 Bq/kg (7 times greater than the global average value). Based on field observation, the P15 sand sample was collected at the Sai Thong beach near a famous shrine. Many sacrificial statues made from concrete and rock have been placed at this shrine for sacred worship (Figure 3b). Therefore, the abnormally high ^{226}Ra concentration is possibly caused by these concrete and rock statues, which can be a high source of NORMs [34].

Table 3. Gamma spectrometric measurements of ^{226}Ra, ^{232}Th and ^{40}K activity concentrations and hazard indices (D_{out}, E_{out} and Ra_{eq}) in sand samples

Sample	**Specific activity (Bq/kg)**			D_{out}	E_{out}	Ra_{eq}
no.	^{226}Ra	^{232}Th	^{40}K	nG/h	mSv/y	Bq/kg
P2	117.03±0.18	51.88±0.08	319.74±0.48	98.06	0.12	215.84
P3	250.95±0.38	120.87±0.18	571.07±0.86	211.73	0.26	467.76
P4	39.94±0.06	15.14±0.02	194.25±0.29	35.43	0.04	76.55
P5	213.84±0.32	112.97±0.17	91.22±0.14	170.02	0.21	382.41
P6	42.09±0.06	14.26±0.02	156.01±0.23	34.12	0.04	74.50
P7	72.16±0.11	34.75±0.05	369.25±0.55	69.70	0.09	150.29
P8	41.76±0.06	14.22±0.02	143.81±0.22	33.43	0.04	73.17
P9	50.06±0.06	24.57±0.04	425.64±0.64	55.94	0.07	117.97
P10	33.98±0.05	14.08±0.02	172.08±0.26	31.23	0.04	67.36
P11	58.01±0.09	28.15±0.04	320.91±0.48	57.21	0.07	122.98
P12	39.27±0.06	15.88±0.02	286.53±0.43	39.60	0.05	84.04
P13	42.98±0.06	18.05±0.03	205.92±0.31	39.16	0.05	84.65
P14	49.49±0.07	21.25±0.03	221.85±0.33	44.74	0.05	96.96
P15	285.93±0.43	27.43±0.04	360.55±0.54	155.75	0.19	352.91
Av.	95.53±0.14	36.65±0.05	274.20±0.41	76.87	0.09	169.10
Max.	285.93±0.43	120.87±0.18	571.07±0.86	211.73	0.26	467.76
Min.	33.98±0.05	14.08±0.02	91.22±0.14	31.23	0.04	67.36
S.D.	87.51	35.57	130.28	59.34	0.07	133.71

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Table 4. International guidance and parametric values of NORMs in sediment

Directive/ recommendation	Value limits	Reference
Dose limit	1 mSv/y	ICRP,2007 [24]
Radium equivalent activity	370 Bq/kg	UNSCEAR, 2000 [3]
The world average of ^{226}Ra	40 Bq/kg	UNSCEAR, 2000 [3]
The world average of ^{232}Th	40 Bq/kg	UNSCEAR, 2000 [3]
The world average of ^{40}K	370 Bq/kg	UNSCEAR, 2000 [3]

Figure 3. a) Sampling sites at Pradu Bay; b) Local shrine at P15 sampling site

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From Table 4, the ^{232}Th activity concentration in sand samples ranges between 14.08±0.02-120.87±0.18 Bq/kg. Most sand samples have ^{232}Th concentration below the global ^{232}Th average value of 40 Bq/kg. The maximum ^{232}Th concentration of 120.87±0.18 Bq/kg (3 times higher than the global average value) is found in sediment collected from Klong Takuan (P3, Figure 3a), while the sand sampled at an aquacultural community (P5, Figure 3a) shows the second-highest ^{232}Th concentration of 112.97±0.17 Bq/kg. With an average value of 36.65±0.05 Bq/kg, the ^{232}Th concentration presented in this study is lower than the global average value. The ^{40}K activity analysis results show that concentrations of ^{40}K activity along the study area are higher than those of ^{226}Ra and ^{232}Th, as expected in normal sediment [35]. The ^{40}K concentration varies between 91.22±0.14-571.07±0.86 Bq/kg, with average value of 274.20±0.41 Bq/kg, which is lower than the global ^{40}K average value of 370 Bq/kg. Again, the maximum ^{40}K concentration (571.07±0.86 Bq/kg) is found at Klong Takuan (P.3). However, this is still lower than the maximum concentration found along the Andaman coast (655 Bq/kg), one of the most charming attraction zones in Thailand [36]. As the maximum concentrations of ^{226}Ra, ^{232}Th and ^{40}K activities are found in sediment from Klong Takuan, industrial activities may contribute some NORMs to the sea. However, the average value of each parameter is below the global average and the impact of high NORMs may be diminished by coastal processes such as water circulation by tides and waves.

The calculated annual outdoor effective dose rate (E_{out}) in each sand sample is reported in Table 3. The E_{out} ranges between 0.04-0.26 mSv/y (Figure 4a), which is lower than the dose limit of 1 mSv/y recommended by ICRP [24]. The radium equivalent activity (Ra_{eq}) in most samples (Table 3, Figure 4b) does not exceed the international allowed limit of 370 Bq/kg recommended by the UNSCEAR [3]. However, samples taken on the beach near Klong Takuan (P3 and P5) have Ra_{eq} values slightly above the recommended limit. Local communities living along the coast are therefore subjected to a low risk of radiation hazard. Tourists who generally spend significantly less time in the area than local people, however, should not be harmed by NORMs at the beaches along the study area.

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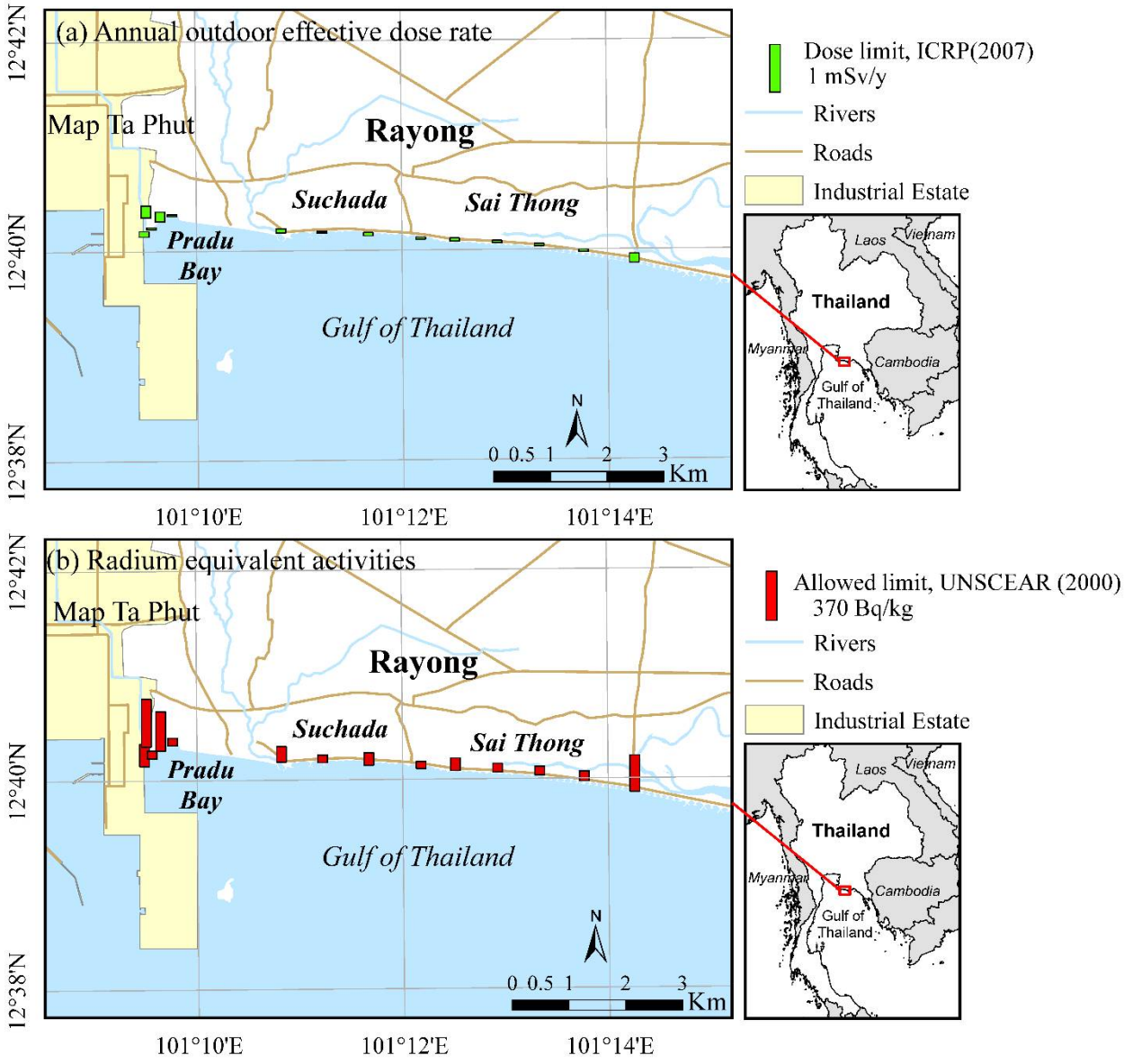

Figure 4. Radiological risk map: a) Annual outdoor effective dose rate (E_{out}); b) Radium equivalent activities (Ra_{eq})

CONCLUSIONS

Industrial activities in the MTP complex have not generated harmful levels of NORMs in sea water. Results also reveal that ^{226}Ra and ^{232}Th activity concentrations in beach sand along the study area are generally lower than the international guidance values, except for two locations (P3 and P5) near Klong Takuan (the MTP drainage channel). Based on estimated radium equivalent activity (Ra_{eq}) in the sand samples, these two spots have a higher Ra_{eq} than the recommended values. However, the estimated annual effective dose (E_{out}) in all sand samples varies between 0.04-0.26 mSv/y, which is lower than the suggested dose limit of 1 mSv/y. Industrial activities in the MTP Industrial Estate during the past decades have therefore not contributed the radiometric risk to aquaculturists, tourists and people from the local communities who spend time at the coastal zone from Pradu Bay to Sai Thong beach.

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