Modeling Environmental Impact Factor of Harmful Chemical Compounds in Polluted Water Discharge in Offshore Installations

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Abstract

The development of a novel model to study the fate and environmental impact factor (EIF) of harmful chemical compounds in polluted water discharges from an offshore installation in Nigeria's marine environment was carried out in this study. The developed numerical fate model incorporates the environmental impact factor, k_F*, derived stochastically on a specific fuzzy logic-based framework, and the boundary value problem of the resulting fate and EIF model was solved via finite element method in MATLAB environment and the Dose-related Risk and Effects Assessment Model (DREAM) software using prevailing field and meteorological conditions of the marine environment. The fate concentrations of oil dispersants, harmful heavy metals (such as copper and mercury), and aromatic compounds (such as naphthalene, benzene-toluene-ethylbenzene-xylene (BTEX)) simulated at polluted water discharge rates of 3,000, 5,000, 25,000 and 75,000 barrels/day (bpd)) and average temperature of 27°C were used to compute EIFs of harmful chemical compounds in the marine environment. The results showed the produced water (PW) discharged volume and the corresponding EIF. For produced water discharge rates of 3,000, 5,000, 25,000 and 75,000 bpd, the simulated EIFs are 0, 5.6135,* 5.3072×10^7 *and* 3.7150×10^8 *respectively, which is indicative of environmental risk far greater than the commonly accepted 5% risk margin in the water column in the cases of 5,000, 25,000 and 75,000 bpd. Higher risk impact derived from higher discharge rates may be effectively handled by water dilution and transport.*

Keywords: *Fate, Environmental impact factor, Polluted water, Offshore installation, Marine environment.*

1. Introduction

Produced water (PW) constitutes part of the liquid phase (i.e., formation and injected waters) when crude oil is extracted from sub-sea reservoirs of hydrocarbons. Hence, these waters embody an extremely complicated mixture of dispersed crude oil, alkylphenols, ketones, aromatic hydrocarbons, dissolved gases, heavy metals, suspended particles, salts, organic acids, added production chemicals

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and naturally occurring radioactive materials [1]. Therefore, inorganic and organic materials, which are hazardous pollutants, are contained in produced water arising from the production of oil and gas, and thus cannot be discharged directly to the marine environment. The indiscriminate discharge of produced water induces damage to the environment thereby exterminating the life of water and plants. This practice is amongst the enormous deliberated or unguided industrial discharges to the worldwide marine environment [2, 4], which contain 4,000 tons of crude oil, with yearly discharges in the North-Atlantic area of 300×106 m^3 [4, 5]. o, before discharging the produced water into the surrounding ocean, it can either be re-injected into the formation or treated to meet the regulation limit for offshore operations.

Though dispersed crude oil and polycyclic aromatic hydrocarbons (PAH) account for a minute fraction of the discharge of total produced water, whereby they cause toxicity to sensitive early life stages of pelagic-spawning fish, wild-caught haddock (*Melanogrammus aeglefinus*) [6, 7], they are significant contributors to risk components of produced water [5, 8] with 15% and 20% to total risk, as revealed by Smit et al. [9] and Ditlevsen [10] respectively. The abduction of deoxyribonucleic acid (DNA) as a priority biomarker for exposure to hazardous PAHs exposure is due to the observed increased concentrations in haddock [5].

An environmental impact factor (EIF) is a specified volume of water where the ratio of no-effect concentration (NEC) to environmental concentration for a particular chemical species is less than 1, thereby constituting an environmental threat to the ecosystem. Diverse chemicals employed in identical offshore applications have been proven to be contributors to the values of EIF and pose unsatisfactory environmental risks to the marine environment [5, 11, 12].

There are several documented models in the literature used to compute environmental impact factors (EIFs) and the fate of harmful chemical compounds in produced (or polluted) water discharge in marine environments [13–18]. More recently, modeling the fate and effects of harmful chemicals in polluted water discharge in marine waters has been extensively studied using suitable software simulators [19–30]. One such simulator is DREAM, which is used to model environmental risks associated with operational discharges of complex mixtures [7, 30–35]. DREAM is a three-dimensional and time-variant numerical model, which can compute transport, exposure, dose, and effects in the marine environment. Equally, the model simulates complicated mixtures of chemicals. Each chemical species in an outflow mixture is described by a set of toxicological, chemical and physical parameters. DREAM incorporates a complete surface slick model as well as the processes governing contaminant characteristics and fates in the water column owing to the fact that petroleum hydrocarbons constitute a major fraction of many industrial releases. The main features of the current version of DREAM 2.0 incorporate exposure, uptake, depuration, and effects for fish and zooplankton simultaneously that have been exposed to complex mixtures of chemicals, with physicochemical transport and fates. The environmental impact factor (EIF) was first developed for the water column. However, it has been extended to include ecological stresses in the benthic community. The EIF is a standardized approach for the assessment of risk associated with the marine environment and does not demand detailed information on the local biological resources, which thus makes the methodology suitable for new geographical areas. Hence, it has been applied to Africa, southern and northern Europe, and South and North America's waters. However, the main drawback of DREAM is that the governing physical-chemical processes are accounted for independently for each chemical species in the mixture. Thus, complex data analysis is required to compute the risk of exposures and impact of each chemical compound in polluted water discharged in adjoining environments. This makes the computations of EIFs very tedious and expensive. Furthermore, horizontal and vertical dilution and transport, dissolution resulting from droplet form volatilization from the dissolved or surface phase, particulate adsorption/desorption and settling, degradation, and segregation are very difficult to track. Therefore, computations of the fate models require several interactions of data to arrive at credible scenarios [13, 30, 36–37]. The other models used to simulate polluted water transport fate and effect, such as Proteus, Provann, and OOC are limited by a lack of an intermediate transport module, which is important in the accuracy of the far-field mixing. CORMIX software [19, 20–27, 29] and the new version of DREAM are the only models that consider the intermediate mixing process. To resolve the shortcomings of previous models, we have proposed an improvement on the existing fate and effect models by incorporating EIF derived stochastically on a specific fuzzy logic framework in the numerical fate model. Thus, by redefining EIF as a set of random variables of linguistic fuzzy classifications to model the governing physical-chemical processes accounted separately for each chemical in the mixture, we were able to simulate the fate and EIF of the interactions of complex hazardous mixture with limited data using prevailing field and metrological conditions of the marine environment. However, DREAM is a well-validated software model with field data and has been confirmed by industry users and regulators, hence, the justification for its reliability for computing fate and EIF, as carried out in this study.

2. Model development and methodology

The fate of harmful heavy metal compounds of polluted water discharged into the marine offshore environment is governed by the following fate processes: (i) Advection/diffusion; (ii) Spreading; (iii) Evaporation; (iv) Dissolution (or entrainment); (v) Emulsification; (vi) Sedimentation (or sinking); (vii) Photo-oxidation (or photolysis); (viii) Biodegradation; and (ix) Shoreline interaction. The fate model is the generalized transport equation given by Equation (1) [18]:

$$\frac{\partial c_i}{\partial t}+\vec{V}.\vec{\nabla}c_i=\vec{\nabla}.D_k\vec{\nabla}c_i+\sum_{j=1}^{n}r_jc_i+\sum_{j=1}^{n}\sum_{i=1}^{n}r_{i,j}c_i+S_i \tag{1}$$

Where c_i is the *ith* chemical constituent concentration in the release, t the time, $\vec{V}$ the adjective transport vector, $\vec{\nabla}$ the gradient operator, D_k the turbulent dispersion coefficient in k (= x, y, z) directions, r_i the process rates, including (i) addition of mass from continuous release, (ii) evaporation from surface slicks, (iii) spreading of surface slicks, (iv) emulsification of surface slicks, (v) deposition from water surface onto coastline (beaching), (vi) entrainment and dissolution onto the water column, (vii) resurfacing of entrained oil, (viii) volatilization from water column, (ix) dissolution from sediments to water column, (x) disposition from water column to bottom sediments, (xi) removal from coastline to water column/water surface, and (xii) mass removal by clean-up, $r_{i,j}$ the degradation terms [18] and S_i the source discharging polluted water component *i*. The source discharging polluted water component *i*, S_i, in g mol/(m^3 s), is given by:

$$S_i=\frac{W}{A_x\Delta x M_i} \tag{2}$$

Where W is mass rate $(=\rho v)$, g/s. ρ the density of component *i*, g/cm^3, v the volumetric flowrate, cm^3/s, A_x the cross-sectional area, m^2, Δx the infinitesimal change in length, m, and M_i the molecular weight of component *i*, g/g mol.

The environmental impact factor (EIF) is an environmental index to quantify the risk of environmental damage from polluted water discharged into the marine environment. EIF is based on a combined environmental risk and hazard assessment, accounting for both the composition and amount of the polluted water discharged. It is based on major principles of risk and hazard assessment. The risk assessment is based on the EIF (predicted effect concentration, PEC/predicted non-effect concentration, PNEC) approach. A standard set of PNEC values for the polluted water groups of chemical compounds representing the naturally occurring compounds is established based on available toxicity data in the literature. For man-added chemicals, a calculation method based on the Harmonized Offshore Chemical

Notification Format (HOCNF) data is used. For a PEC/PNEC ratio higher than 1, unacceptable effects will most likely occur due to exposure to the specific chemical. The total risk of polluted water is based on the summation of the risk of the sub-groups. The multi-media transport process predicts a non-steady state for a far-field model. The dispersion process of polluted water in a non-steady environment, given by Equation (1), has been modified with the incorporation of the environmental impact factor (EIF), k_F, in the fate model.

$$\left(1+k_F\right)\frac{\partial c_i}{\partial t}+\vec{V}.\vec{\nabla}c_i=\vec{\nabla}.D_k\vec{\nabla}c_i+\sum_{j=1}^{n}r_j c_i+\sum_{j=1}^{n}\sum_{i=1}^{n}r_{i,j}c_i+S_i \tag{3}$$

The predicted environmental impact factor, $(k_F)_{pred}$, is given by Equation (4).

$$(k_F)_{pred}=Rand(0,\,1)\left(\frac{PEC}{PNEC}\right) \tag{4}$$

Equation (3) is subject to the initial conditions:

$$c_i(x=0,\,t)=c_{i0} \tag{5}$$

$$c_i(y=0,\,t)=0 \tag{6}$$

$$c_i(z=0,\,t)=0 \tag{7}$$

and the boundary conditions given in Equations (8)–(10):

$$\frac{\partial c_i}{\partial x}(x=L,\,t)=0 \tag{8}$$

$$\frac{\partial c_i}{\partial y}(y=y,\,t)=0 \tag{9}$$

$$\frac{\partial c_i}{\partial x}(x=L,\,t)=0 \tag{10}$$

The modified fate model, given by Equation (3), subject to the initial and boundary conditions given in Equations (5)–(7) and (8)–(10) respectively, is solved to generate a matrix-vector form, given in Equation (11), from which the transient state concentration profiles in-depth and radial directions can be obtained, and the drift velocity located. The model is currently being applied to the offshore fields to establish whether a discharge is acceptable or not.

$$\underbrace{\begin{bmatrix} d & b & a & 0 & 0 & \cdots & 0 & 0 & 0 \\ 0 & d & b & a & 0 & \cdots & 0 & 0 & 0 \\ 0 & 0 & d & b & a & \cdots & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & 0 & \cdots d & b & a \end{bmatrix}}_{\underline{A}} \underbrace{\begin{bmatrix} c_0 \\ c_1 \\ c_2 \\ c_3 \\ \vdots \\ c_{m-1} \\ c_m \\ c_{m+1} \end{bmatrix}^{n+1}}_{\underline{X}} = \underbrace{\begin{bmatrix} C_1 \\ C_2 \\ C_3 \\ C_4 \\ \vdots \\ C_m \end{bmatrix}^{n}}_{\underline{X}} + \underbrace{\begin{bmatrix} Bs_1 \\ Bs_2 \\ Bs_3 \\ \vdots \\ \vdots \\ B_{Sm} \end{bmatrix}}_{\underline{B}} \tag{11}$$

Hence, $\underline{A}\,\underline{X}^{n+1} = \underline{X}^{n} + \underline{B}$

$$\therefore\ \underline{X}^{n+1} = \underline{A}^{-1}\underline{X}^{n} + \underline{A}^{-1}\underline{B} \tag{12}$$

2.1. Model input data

The field studied in this work is a Nigerian oil and gas field located in an offshore block in the Gulf of Guinea. The field is located close to shore, approximately 45 km from land. The depth of water in the area is approximately 55 m. The coordinates of the field installation used for the EIF calculations are: North: 04 degrees, 06 minutes, 19 seconds. East: 08 degrees, 10 minutes, 37 seconds. The discharge depth is 20 m below the surface. The base case study for Nigerian field development assumes continuous discharge of produced water (PW) for 28 days (based on 90% availability) into the sea after being treated according to industry standards. This is a single occurrence using four peak-produced water discharge rate scenarios of 3,000 barrels/day (bpd) (477 m^3/day), 5,000 barrels/day (795m^3/day), 25,000 barrels/day (3975 m^3/day) and 75,000 barrels/day (11,925 m^3/day) to determine the potential environmental risk and contributors to that risk as the best operating, for the design and the worst cases. The model simulations, based on field data for Nigerian field installation in Offshore Nigerian Waters, were carried out in line with the published EIF methodology and project objectives for these four discharge case scenarios. Table 1 shows the meteorological data, which are coordinates of the study location used in the simulation.

Table 1. Coordinates of the study location

Sample Code	Latitude	Longitude
FS-1	4^{o} 06’ 08.13”N	8^{o} 10’ 26.69”E
FS-2	4^{o} 06’ 11.38”N	8^{o} 10’ 26.69”E
FS-3	4^{o} 06’ 04.86”N	8^{o} 10’ 26.69”E
FS-4	4^{o} 06’ 08.13”N	8^{o} 10’ 29.96”E
FS-5	4^{o} 06’ 08.13”N	8^{o} 10’ 23.46”E
FS-6	4^{o} 06’ 05.90”N	8^{o} 10’ 29.09”E
FS-7	4^{o} 06’ 14.50”N	8^{o} 10’ 26.37”E
FS-8	4^{o} 06’ 01.87”N	8^{o} 10’ 26.58”E
FS-9	4^{o} 06’ 08.35”N	8^{o} 10’ 33.00”E
FS-10	4^{o} 06’ 08.31”N	8^{o} 10’ 20.02”E
FS-11	4^{o} 06’ 03.97”N	8^{o} 10’ 31.29”E
FS-12	4^{o} 05’ 57.14”N	8^{o} 10’ 38.06”E
FS-13	4^{o} 05’ 45.91”N	8^{o} 10’ 50.42”E
FS-14	4^{o} 05’ 01.68”N	8^{o} 11’ 39.49”E
FS-15	4^{o} 04’ 18.99”N	8^{o} 12’ 27.21”E

Table 2 shows water composition and concentration of chemicals in installation used as case study. Oil and grease and total hydrocarbon content (THC) have the highest concentration of 38.65 mg/L and 36.5 mg/L and the other chemicals: benzene-toluene-ethylbenzene-xylene (BTEX), aromatics derivatives, copper, lead, nickel are present in amounts less than 0.1 mg/L, while mercury occurs in trace amount less than 0.001 mg/L.

Table 2. Produced water composition for Nigerian field installations PRD Lease-67

Parameters	**Concentration (mg/L)**
Dispersed Oil	0
BTEX	0.156
Naphthalene	0.0979
Acenaphthylene	0.0979
PAH 2–3 ring	0
PAH 4–ring +	0
Phenols (C0–C3)	0
Phenols (C4–C5)	0
Phenols C6	0
Heavy Metals	0
Zinc (Zn)	0
Copper (Cu)	0.068
Nickel (Ni)	0.616
Cadmium (Cd)	<0.001
Lead (Pb)	0.0014
Mercury (Hg)	<0.001
Chromium (Ch)	0.095
Vanadium (V)	0.054
Barium (Ba)	0.036
Anthracene	0.0733
Phenanthrene	0.1127
Fluoranthene	0.7052
Benzo(b) Fluoranthene	0.4809
Chrysene (1,2-benzphenanthrene)	0.0682
Benzo(b) fluoranthene	0.0413
Benzo(a) pyrene	0.0601
Benzog,h,c)	Not Determined
Indino (1,2,3 – cd)	Not Determined
Total hydrocarbon concentration (THC)	36.5
Oil and Grease	38.65
PAH	1.6396

The composition and physical data used in the simulation to derive EIF are displayed in Table 3. The diffusivity constant of each component at 27°C, decay constant and initial concentration were obtained from the GSI chemical properties database.

Table 3. Data used in the simulation

Components	**Diffusivity constant at 27°C (cm^2/s)**	**Decay constant, (s^{-1})**	**Relative molecular mass**	**Initial concentration (mg/L)**
Naphthalene	7.5×10^{-6}	5.347×10^{-6}	128.1705	0.0979
BTEX	9.8×10^{-6}	1.604×10^{-5}	99.5384	0.1560
Copper	7.14×10^{-6}	0	63.546	0.0680
Mercury	6.3×10^{-6}	0	200.59	0.001

In Table 3, the relative molecular mass of BTEX was obtained thus by considering the average weight percentages of its compounds, which are approximately 1.9% benzene (of molar mass 78.11 g/mol), 4.7% toluene (of molar mass 92.14 g/mol), 2.0% ethylbenzene (of molar mass 106.16 g/mol) and 9.4% xylene (of molar mass 106.16 g/mol):

Relative molecular mass of BTEX = $1.9\times78.11+4.7\times92.14+2.0\times106.16+9.4\times106.16/18$ =99.5384

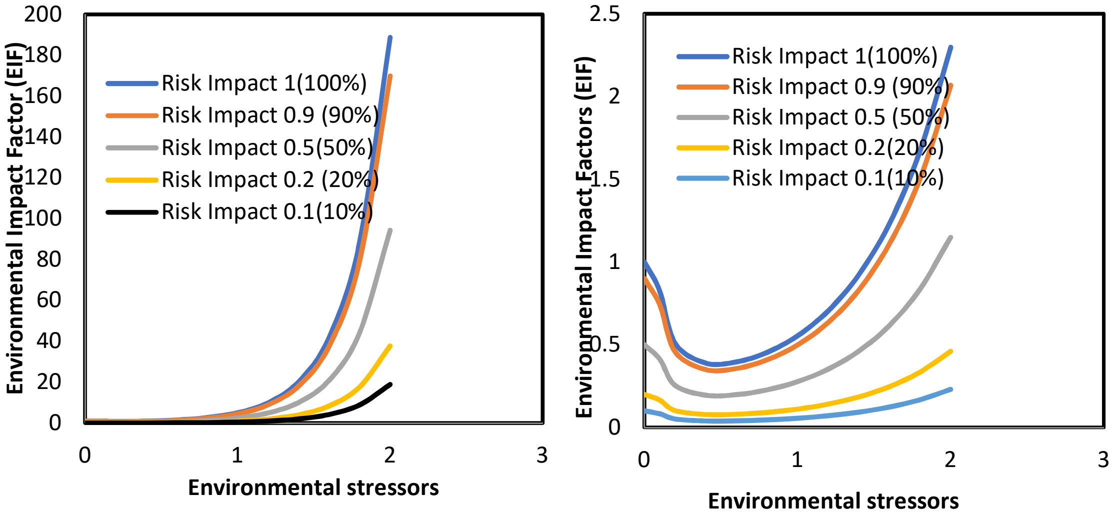
3. Simulated results and discussion

The produced water (PW) simulation was studied for the density of polluted water of 1030.0kg/m^3, the discharge rates 477 m^3/day (3,000 barrels/day), 795 m^3/day (5,000 barrels/day) and 3,975 m^3/day (25,000 barrels/day), and 11,925 m^3/day (75,000 barrels/day), and the temperature at an average value of 27°C. The bottom current velocity is 3.66 m/s. The transport model developed was solved using the finite element method because the transport problem is a boundary value problem in the MATLAB environment. The predicted concentration was done within sampling coordinates (FS1-FS15), as presented in Table 1. Also, the turbulent diffusivity constant in the *x, y* and z directions are equal, i.e., $D_x = D_y = D_z\ (= D)$ The marine environment is assumed to be isothermal. Equally, there is no chemical reaction owing to the fact that the effect of degradation among the constituents of interest is more pronounced than the chemical reaction involved.

3.1. Environmental impact factor

The environmental impact factor (EIF) was simulated using the DREAM software and the MATLAB program to predict the fate of polluted water discharges. Figures 1(a) and 1(b) show the environmental impact factor against environmental stressors of fuzzy classes 1 and 2, i.e., very likely and likely respectively to impact the marine environment at different risk levels for the polluted discharges.

The environmental stressors represent the dose of polluted compounds in the marine environment. From Figure 1(a), the risk impact level 1 (100%) produces the highest environmental impact factor that could be experienced with an environmental stressor (dose) of the parametric value of 2, which gives an environmental impact factor of 186. The risk impact level 0.1 results in the lowest EIF profile. A different trajectory of EIF where the highest risk impact produces an EIF significantly reduced to less than 2.5 for an environmental stressor–dose impact of 2.0. A change in fuzzy classification from 1 (very likely) to fuzzy class 2 (likely) changed the exponential trajectory of Figure 1(a) to a parabolic trajectory observed in Figure 1(b). For the fuzzy class 3, i.e., unlikely scenario, there is no impact of EIF against environmental stressors at different risk levels, though the results are not presented in this paper.

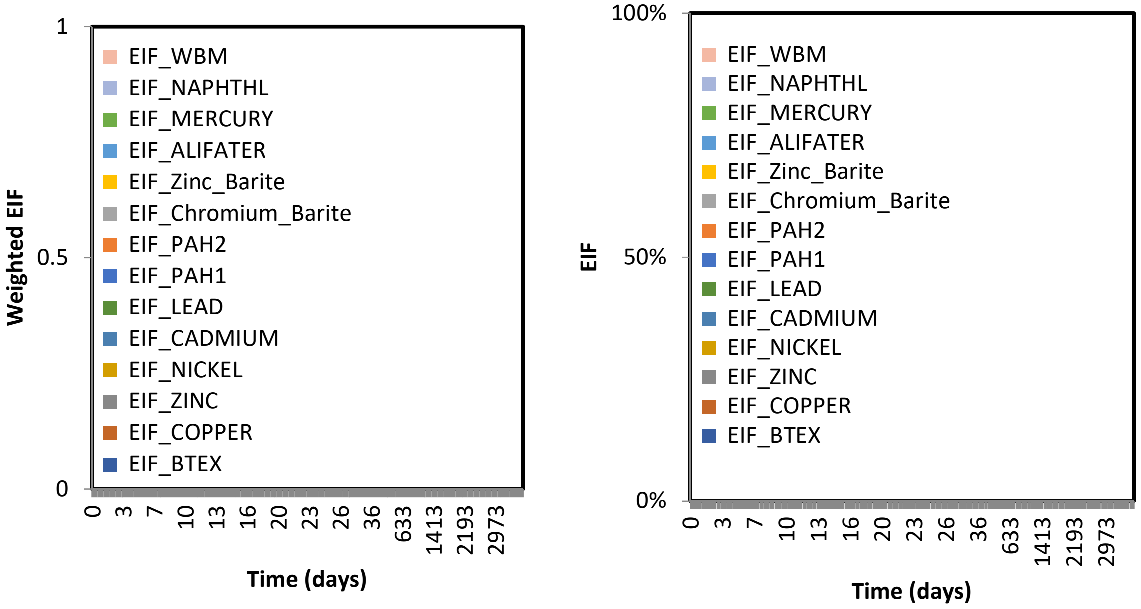


(a) (b)

Figure 1. Environmental impact levels class representation for (a) fuzzy class 1 (very likely), and (b) fuzzy class 2 (likely) to impact the environment.

3.2. Time development charts

Figure 2(a) shows a simulation of the EIF development chart for produced water (PW) discharged at a rate of 3,000 barrels/day.



(a) (b)

Figure 2. Time development, (a) EIF (weighted EIF) for a discharge case of 3,000 barrels of produced water/day, and (b) EIF (EIF %) for a discharge case of 5,000 barrels of produced water/day.

The charts in Figure 2 show the EIFs are zero at all times. Hence, there is no significant impact of the EIF on the marine environment at a discharged rate of 3,000 barrels/day. Figure 2(b) shows the time development chart at a discharge rate of 5,000 barrels of produced water/day. The primary contributors to the EIF are copper and polycyclic aromatic hydrocarbons (PAH2) compounds.

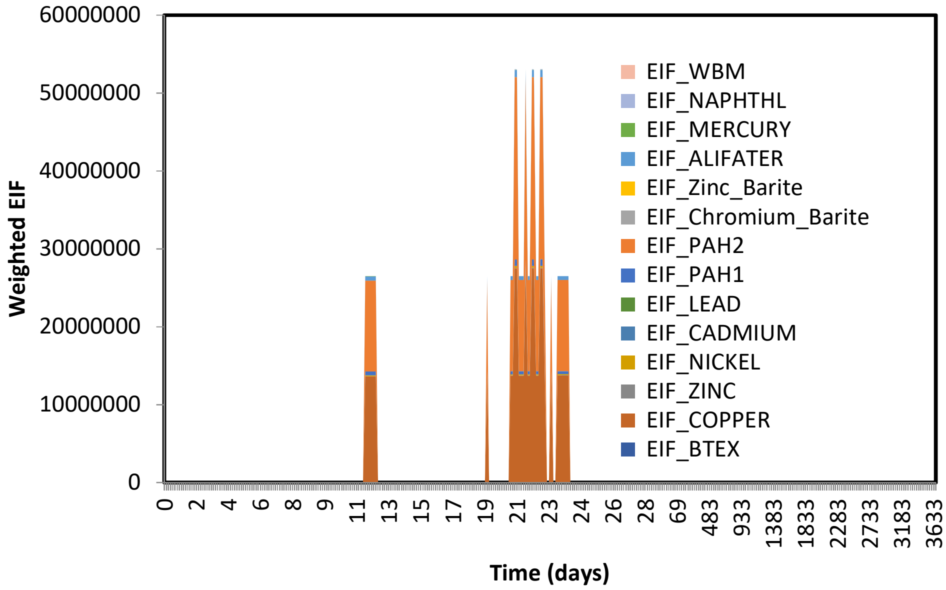
Figures 3(a) and 3(b) are the respective plots of EIF and % EIF profile with time for the discharge rate of PW at 25,000 barrels/day (3975 m^3/day) simulation case. DREAM predicted that the weighted EIF and % EIF of the time development chart for PW – copper, BTEX and PAH2 would increase from zero to significant values, where weighted EIF is typically in the range of 5.5×10^7, thereby indicating risk of more than 5% impact to the water column to be expected. However, from the plots, DREAM predicted % EIF and weighted EIF of PW chemical species BTEX, lead, chromium, zinc and water-based mud (WBM) is zero. From the plots, the DREAM prognosis showed that EIF of copper, PAH2 and BTEX significantly increased in weighted and % EIF between day 11.75 to day 12.38, 18.88 days and between day 20.25 to day 23.63 except for the first 11 days and the last 4 days, day 24 to day 28. Therefore, an increase in % and weighted EIF for PW chemicals should be expected when the discharge rate is increased from 5,000 to 25,000 barrels/day. Since EIF is greater than 1 in this case, environmental risk greater than 5% should be expected.

The DREAM simulation results of the time development EIF chart and risk profile for PW discharged at a rate of 75,000 barrels/day (11925 m^3/day) from field Installation are presented in Figures 4(a) and 4(b). This discharge rate of 75,000 barrels/day is the worst-case scenario. From Figures 4(a) and 4(b), DREAM predicted the weighted EIF and % EIF are significantly greater than 1 and are in the range of 10^8 for the discharge case of 75,000 barrels/day with copper and PAH2 both having % EIF up to 97%. Therefore, DREAM simulations established that environmental risk far more than the commonly used threshold of 5 % in the water column should be expected for the PW discharge rate of 75,000 barrels/day. From the DREAM prognosis, impacts will be temporary with the risk extending to a maximum of 1 km from the point of discharge; however typically, the area of risk is expected to be much smaller within 1 km^2. This was deduced from the DREAM weighted EIF and % EIF plots of Figures 4(a) and 4(b) as environmental risk is reduced to below levels of concern (typically zero) approximately three days after the end of the discharge cycle of 28 days. DREAM estimated that weighted EIF and % EIF for 75,000 barrels/day is significant after 1 day of discharge increasing up to 31 days, 3 days after the 28 days cycle for all the PW chemicals except BTEX, lead, chromium, zinc and water-based mud (WBM), which is zero.

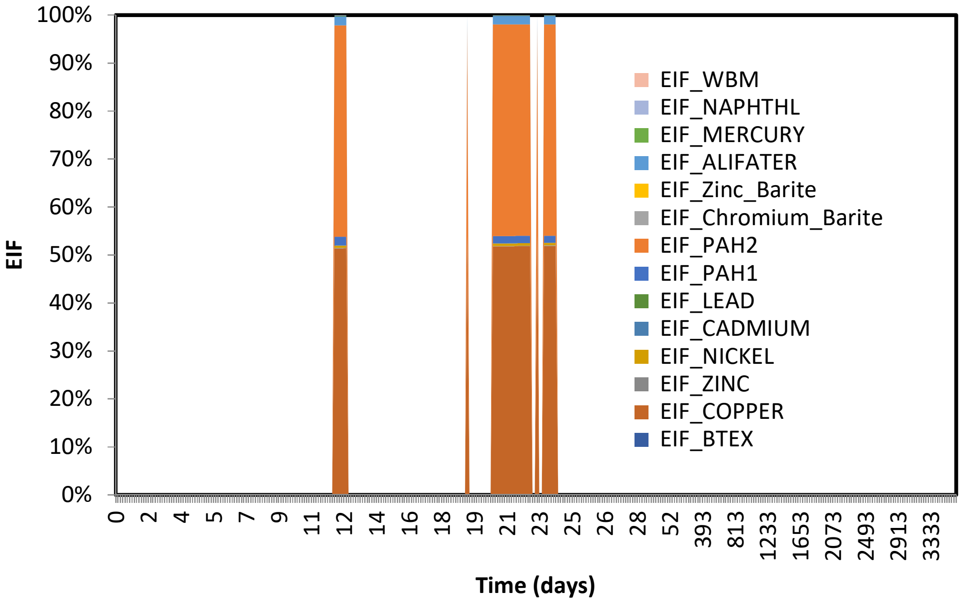
Figure 5 shows the pie chart of EIF at 5,000 barrels of produced water/day. The EIF is 5.6135 for the produced water discharged at 5,000 barrels/day while EIF is 0 at 3,000 barrels/day. There is a total contribution of up to 97% by these compounds to the EIF for produced water (PW) discharged at a projected rate of 5,000 barrels/day. The operation at the best case of 3,000 barrels/day guarantees risk to water column to be within 5%. Higher risk impact derived from higher discharge rates may be effectively handled by water dilution and transport. The time series fate impacts predicted by simulation are temporary and are unlikely not to cause cumulative impacts on sediments bottoms and surface waters. The contribution to EIF of PW chemical compounds, benzene-toluene-ethylbenzene-xylenes (BTEX), lead, chromium barite, zinc barite and water-based mud (WBM) to the water column are all zero for the discharge case of 5,000 barrels/day. Copper and PAH2 have the highest value of EIF of 31554348 and 19659766 respectively at 25,000 barrels/day. Continuous discharge for the first 28 days of production presents a minimal risk to the environment of a risk to the environment >5 %.

Figure 6 shows the pie chart of the weighted EIF contribution to environmental risk for the discharge case of 25,000 barrels/day. From the plots, DREAM predicted that copper has the highest weight contribution to EIF with 60% followed by PAH2 with 37%, while the remaining 3% is contributed by the remaining chemical species in the PW composition profile. Furthermore, the DREAM prognosis showed an increase in EIF to 53071813 from EIF of 5.6135 if discharge rate increased from 5,000 to 25,000 barrels/day. An increased EIF is the result of increased PW discharged rate, indicating more toxic chemical species are carried with larger volume of PW discharge. DREAM results show an

EIF profile greater than 1 around the points of discharge FS1-FS15 and environment risk greater than 5% in the water column should be expected.

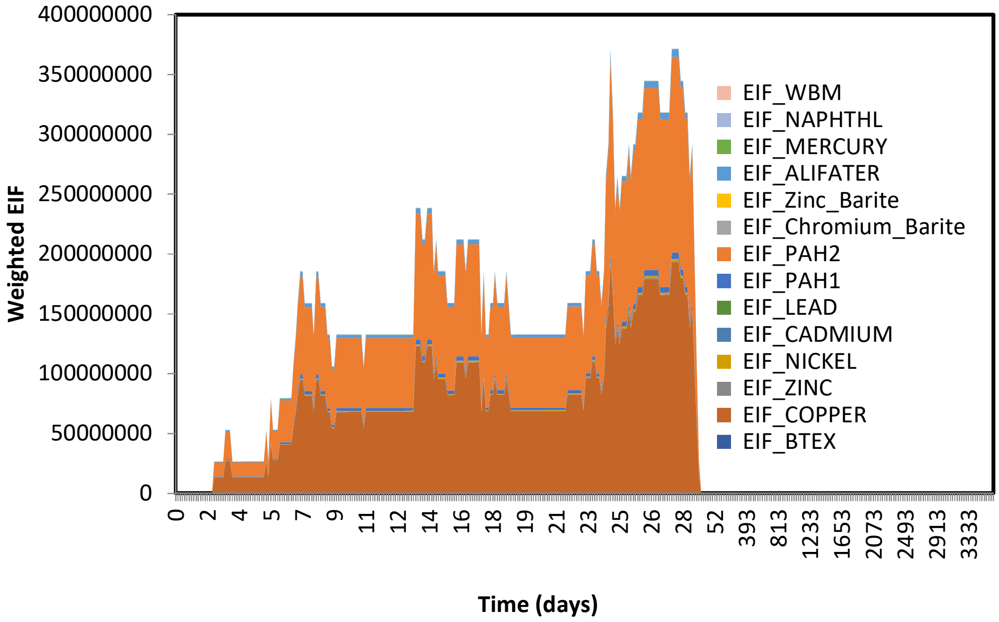


(a)

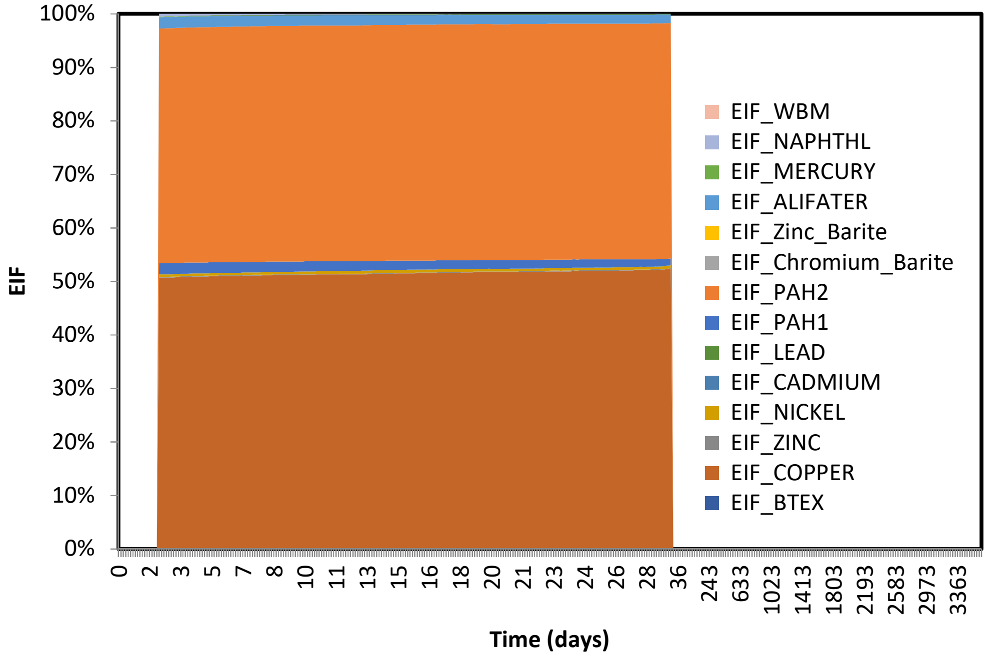


(b)

Figure 3. Time developments, (a) EIF (weighted EIF), and (b) EIF (EIF %) for a discharge case of 25,000 barrels of produced water/day.



(a)



(b)

Figure 4.(a) Weighted EIF with time, and (b) EIF % with time for a discharge case of 75,000 barrels of produced water/day.

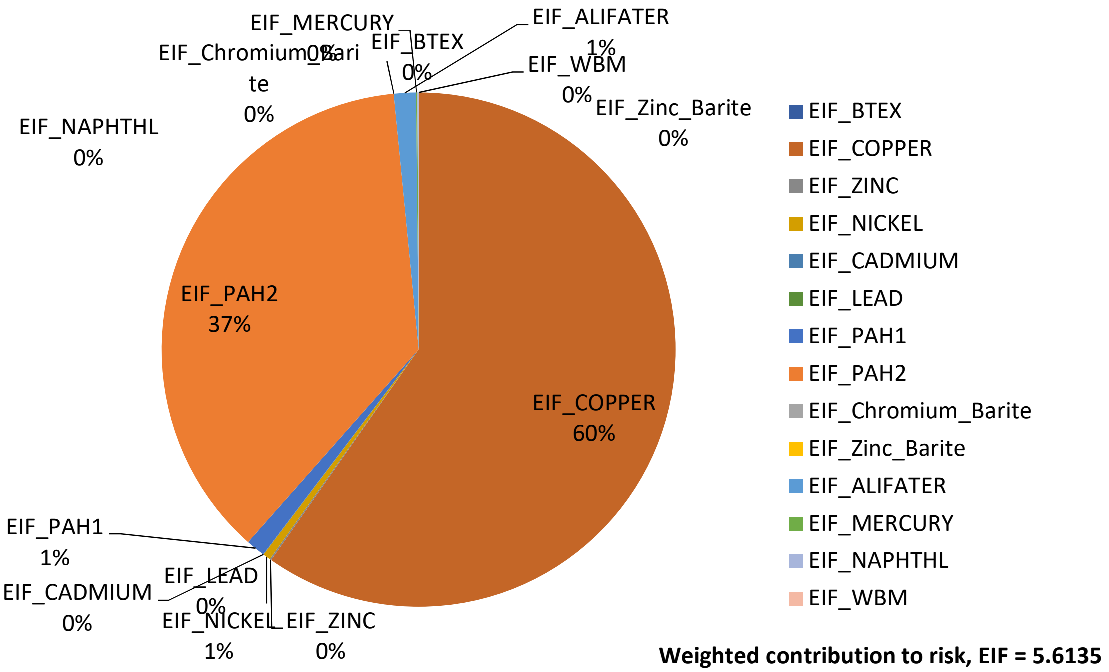


Figure 5. Pie chart weighted contribution to risk for a discharge case of 5,000 barrels of produced water/day.

Figure 7 shows the pie chart of weighted EIF contribution for PW discharged at a rate of 75,000 barrels/day from field installation. From the chart, DREAM predicted that copper and PAH2 are the largest contributors to weighted EIF with values of 60% and 37% respectively. However, the other PW chemicals accounted for only 3% of the risk to the water column. Equally, the predicted EIF is 371502690 for the discharge case of 75,000 barrels/day, which is considered very significant from the DREAM computed EIF of 53071813 for the discharge case of 25,000 barrels/day. This is mainly attributed to the increased volume of discharge rate. Since EIF for this case is more than 1, therefore environmental risk far greater than the commonly accepted 5% risk margin should be expected for the discharged case of 75,0000 barrels/day.

The EIF profile derived from DREAM for a discharge case of 25,000 barrels of produced water/day is presented in Table 4. DREAM predicted that the contribution to EIF of BTEX, lead, chromium, barite, zinc barite and WBM to the water column is zero for PW discharged from field installation in Niger Delta. However, contribution to EIF for copper, zinc, nickel, cadmium, PAH1, PAH2, ALIFATHER, mercury, and NAPHTHL as estimated by DREAM is 31554348, 69000.26, 297231.9, 10615.42, 647540.9,19659766, 732464.3, 53077.12, and 47769.41 respectively, whereby all had EIF greater than 1, therefore posing a risk of more than 5% to the water column. The significance of PNEC in determining EIF is now demonstrated: For very low toxicity stressor factors, of PNEC value of 0.008 ppb, mercury at trace amounts < 0.001mg/L may contribute an EIF as high as 53077.12. For similar reasons, PAH1, which has a PW discharged concentration of 0.2839 mg/L, has an EIF as high as 6475540.9 compared to PAH1 with a concentration of 1355700 mg/L, have an EIF of 19659766. From Table 4, the PNEC value for PAH2 is 0.005, and with a large volume of concentration in PW discharged, an EIF far greater than 1 should be expected.

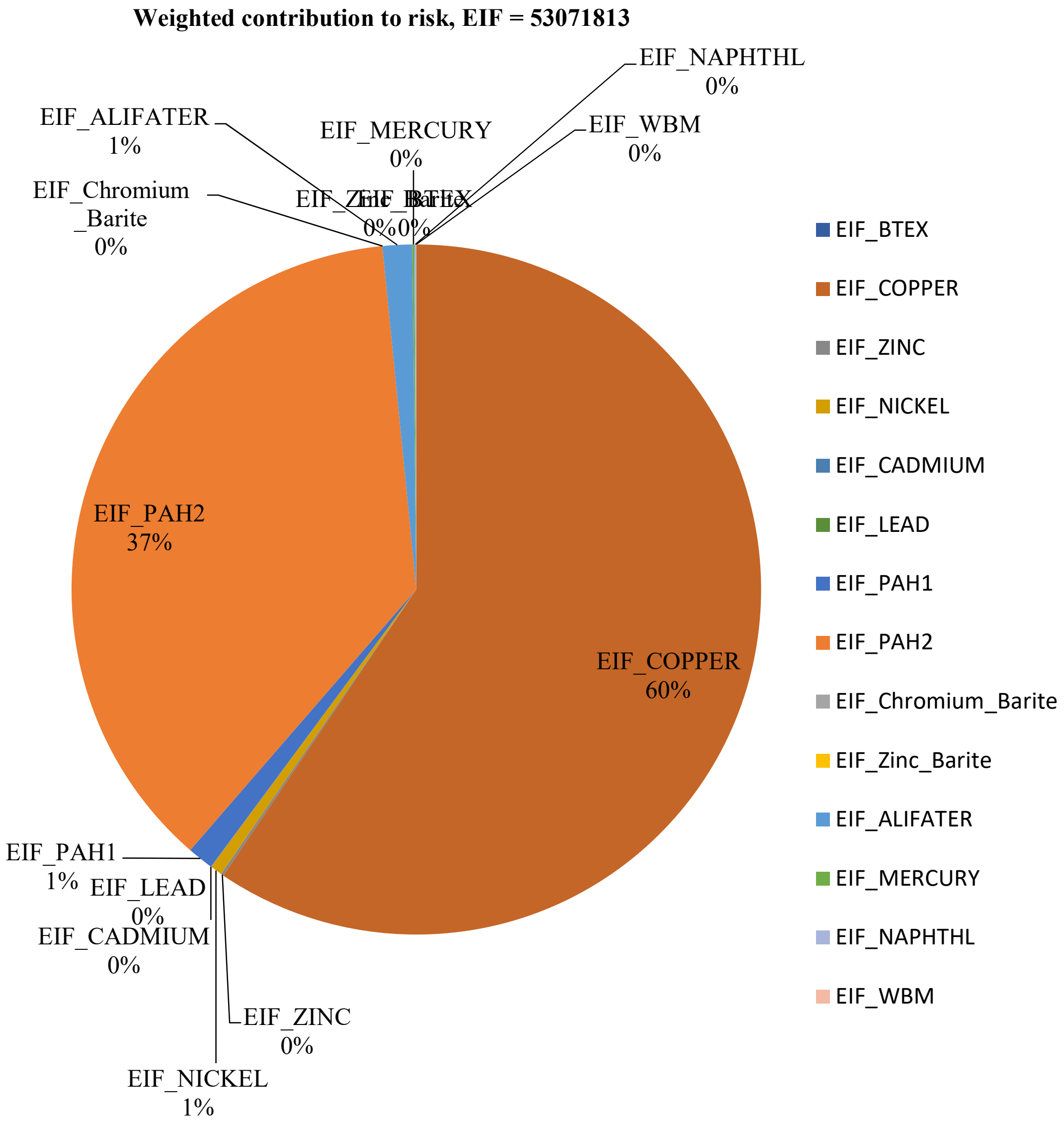


Figure 6. Pie chart weighted contributions to risk for discharge case of 25,000 barrels of produced water/day.

The EIF profile derived from DREAM for a discharge case of 75,000 barrels of produced water/day is shown in Table 5. The contribution to EIF by BTEX, lead, chromium barite, zinc and WBM contribution to EIF are zero at a PW discharge rate of 75,000 barrels/day from the EBOK field installation in OML67. The DREAM prognosis reveals that copper and PAH2 would contribute the highest EIF, with values as high as 2.23×10^{8} and 1.36×10^{8} respectively. Therefore, as the discharge rate increases progressively from 5000 barrels/day to 25,000 barrels/day and 75,000 barrels/day, it is expected that EIF would increase in geometric proportions with environmental risk greater than acceptable margins of 5%. The DREAM prognosis reveals that trace amounts of mercury typically < 0.001 could contribute to EIF as high as 334385.9 since the PNEC threshold of mercury is 0.008. Also, a relatively small concentration of PAH1 of 0.2839 mg/L with PNEC for PAH1 0.15 could have an EIF as high as 4458478, while a large concentration of PAH2 of 1355700 mg/L, which has a comparable low PNEC 0.005, has an EIF contribution of 1.36×10^{8}. These results demonstrate the significance of toxicity and volume of the PW chemicals to EIF.

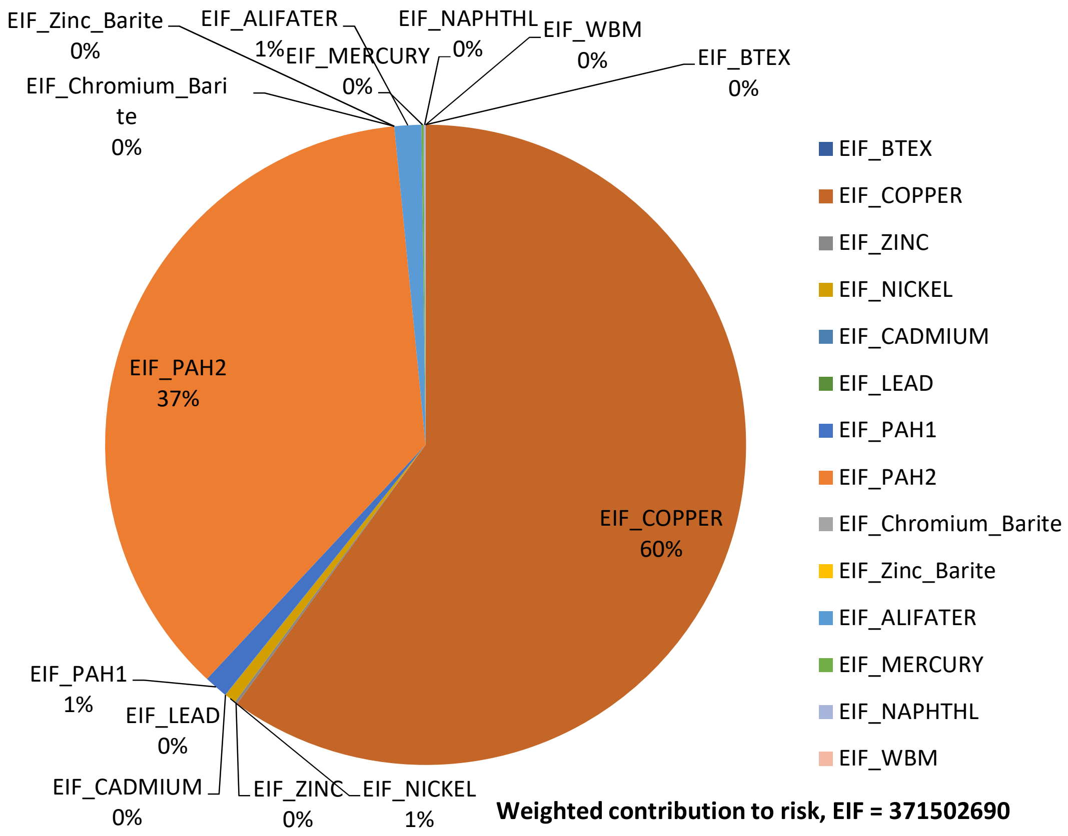


Figure 7. Pie chart of weighted contributions to risk for discharge case of 75,000 barrels of produced water/day.

3.3. EIF with respect to discharge rate

The EIF results were obtained from simulation using a model to generate EIF of produced water discharged from offshore platforms in Nigeria. Table 6 shows the produced water discharge volume and their corresponding EIF. For discharge rates of 3,000 barrels/day, 5,000 barrels/day, 25,000 barrels/day and 75,000 barrels/day for the respective produced water discharge cases 1, 2, 3 and 4, the EIFs are 0, 5.6135, 53071813 and 371502690 respectively. Thus, the EIF is a function of the discharged rate such that the higher the discharge rate, the higher the EIF. The weighted contribution to EIF of PW at 25,000 barrels/day and 75,000 barrels/day discharge from field installation are 53071813 and 371502690 respectively, therefore environmental risks to be far greater than 5% should be expected at these discharge rates.

Table 4. EIF profile for field installation for discharge rate of 25,000 barrels/day

PROFILE(S):EBOK-EIF									
Simulated instantaneous EIF:	**53077121**								
	Product	Relative tons/day	Concentration (ppm)	PNEC (ppb)	Contribution to risk	Contribution EIF	Weight	Weighted contributions	Weighted EIF
Total	PW	4114							53071813.31
EIF_BTEX			0.156	17000000	0	0	1	0	
EIF_COPPER			0.616	0.02	59.45	31554348	1	31554348	
EIF_ZINC			0.068	0.46	0.13	69000.26	1	69000.26	
EIF_NICKEL			0.616	1220000	0.56	297231.90	1	297231.90	
EIF_CADMIUM			0.001	0.028	0.02	10615.42	1	10615.42	
EIF_LEAD			0.0014	0.182	0	0	1	0	
EIF_PAH1			0.2839	0.15	1.22	647540.90	1	647540.90	
EIF_PAH2			1355700	0.05	37.04	19659766	1	19659766	
EIF_Chromium_Barite			0.095	8500000	0	0	1	0	
EIF_Zinc_Barite			0.036	6600000	0	0	1	0	
EIF_ALIFATER			75150000	40400002	1.38	732464.30	1	732464.30	
EIF_MERCURY			0.001	0.008	0.10	53077.12	1	53077.12	
EIF_NAPHTHL			1639600	2100000	0.09	47769.41	1	47769.41	
EIF_WBM			0.054	800000000	0	0	1	0	

Table 5. EIF profile for EBOK field installation in OML 67 for a discharge case of 75,000 barrels of produced water/day

PROFILE(S): EBOK-EIF									
Simulated instantaneous EIF:	**371539844**								
Components	Product	Relative tons/day	Concentration (ppm)	PNEC (ppb)	Contribution to risk	Contribution EIF	Weight	Weighted contributions	Weighted EIF
Total	PW	12343							371502690
EIF_BTEX			0.156	17000000	0	0	1	0	
EIF_COPPER			0.616	0.02	60	2.23E+08	1	2.23E+08	
EIF_ZINC			0.068	0.46	0.14	520155.8	1	520155.8	
EIF_NICKEL			0.616	1220000	0.58	2154931	1	2154931	
EIF_CADMIUM			0.001	0.028	0.02	74307.97	1	74307.97	
EIF_LEAD			0.0014	0.182	0	0	1	0	
EIF_PAH1			0.2839	0.15	1.2	4458478	1	4458478	
EIF_PAH2			1355700	0.05	36.49	1.36E+08	1	1.36E+08	
EIF_Chromium_Barite			0.095	8500000	0	0	1	0	
EIF_Zinc_Barite			0.036	6600000	0	0	1	0	
EIF_ALIFATER			75150000	40400002	1.35	5015788	1	5015788	
EIF_MERCURY			0.001	0.008	0.12	445847.8	1	445847.8	
EIF_NAPHTHL			1639600	2100000	0.09	334385.9	1	334385.9	
EIF_WBM			0.054	800000000	0	0	1	0	

Table 6. Polluted water discharge volume and the respective EIF result from the simulation

Produced water discharge case	Polluted water discharge volume (bpd)	Polluted water discharge volume (m^3/day)	EIF result
1.	3000	477	0
2.	5, 000	795	5.6135
3.	25, 000	3, 975	53071813
4.	75, 000	11, 925	371502690

3.4. EIF with respect to discharged chemicals in produced water

Tables 7–10 show the EIF results with respect to discharged chemicals in the polluted water per discharge rate.

Table 7. EIF for polluted water discharge rate of 3,000 barrels/day

Components	PEC (ppm)	PNEC (ppb)	EIF
Naphthalene	0.0986	2100000	4.695×10^{-5}
BTEX	0.1581	17000000	9.30×10^{-6}
Copper	0.0683	0.02	3415
Mercury	0.0010	0.008	125

Table 8. EIF polluted water discharge rate of 5,000 barrels/day

Components	PEC (ppm)	PNEC (ppb)	EIF
Naphthalene	0.09910	2100000	4.719×10^{-5}
BTEX	0.15840	17000000	9.318×10^{-6}
Copper	0.06920	0.02	3,460
Mercury	0.00101	0.008	126.25

Table 9. EIF for polluted water discharge rate of 25,000 barrels/day

Components	PEC (ppm)	PNEC (ppb)	EIF
Naphthalene	0.1153	2100000	5.49×10^{-5}
BTEX	0.1587	17000000	9.34×10^{-6}
Copper	0.0693	0.02	3,465
Mercury	0.00106	0.008	132.5

Table 10. EIF for polluted water discharge rate of 75,000 barrels/day

Components	PEC (ppm)	PNEC (ppb)	EIF
Naphthalene	0.1376	2100000	6.55×10^{-5}

BTEX	0.1589	1700000	9.35×10^{-6}
Copper	0.0695	0.02	3,475
Mercury	0.00108	0.008	1350

In Table 7, the BTEX has the lowest EIF of 9.30×10^{-6} and copper has the highest EIF of 3415 for the discharged rate of 3,000 barrels/day. While the increase in EIF is marginal for copper, BTEX and naphthalene compounds as the discharge rate increases from 3,000 to 75,000 bpd, EIF of mercury increases significantly from 125 at 3,000 barrels/day to 1,325 at 75,000 barrels/day, as shown in Tables 7–10.

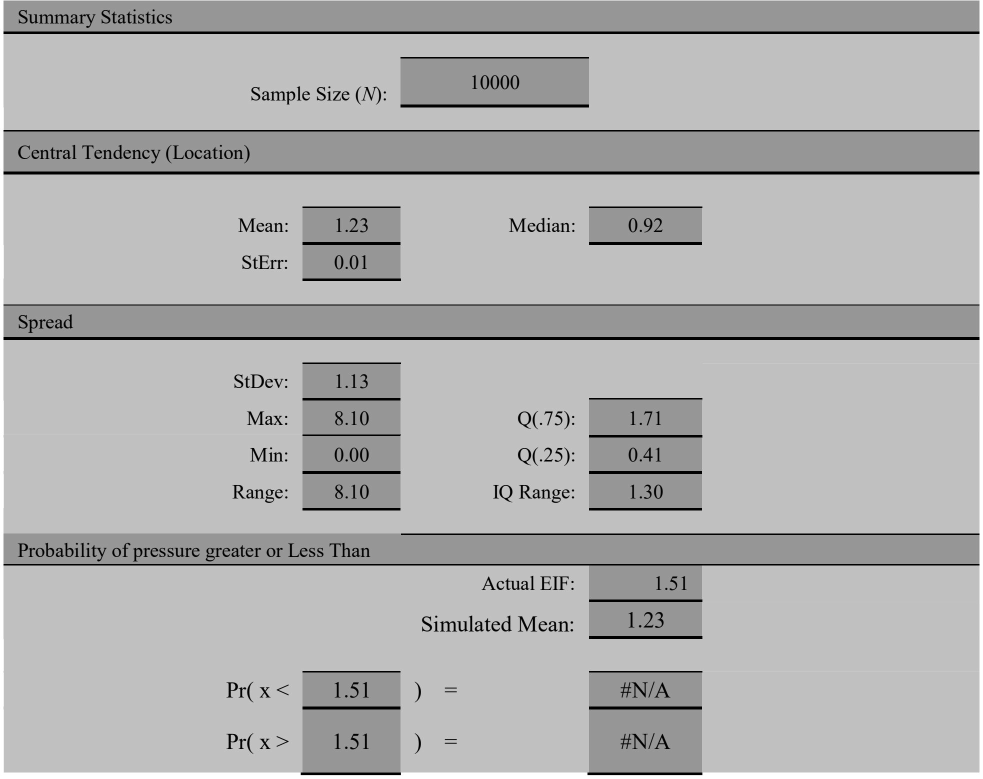
3.5. EIF computation by random table

Table 11 shows the randomly generated environmental impact factor for different random variable ranges, k_L. The k_L factors are the different ranges of EIF variables (0,1), (2,10), (11,50), (51, 100), and (101,500).

Table 11. Environment impact factor (EIF) generated random numbers based on weight toxicity stress factors, k_L, and histogram chart.

S/No.	**RAND** k_L **(0,1)**	**RAND** k_L **(2,10)**	**RAND** k_L **(11,50)**	**RAND** k_L **(51,100)**	**RAND** k_L **(101,500)**	**EIF result**	**Histogram plot**		
	EIF(0, 1)	EIF(2, 10)	EIF(11, 50)	EIF(51,100)	EIF(101, 500)	RAND result			
1	0.47	8.7838	33.0903	68.392	370.9268	2.00	Min:	0	
2	0.65	6.1926	23.3141	76.807	315.9825	1.23	Max:	100	
3	0.87	3.6308	35.1771	69.312	372.5205	1.61	Trials:	5000	
4	0.05	2.8052	24.8281	89.687	242.5713	0.04			
5	0.51	9.5325	44.9374	70.848	481.1135	3.06	Classes	frequency	Cumulative
6	0.66	9.0435	16.7857	66.873	420.6413	1.51	Bins	Count	Probability
7	0.69	3.9519	32.8002	54.838	100.2828	1.63	0	0	0
8	0.47	4.1174	48.8396	68.066	479.9335	1.38	1	2669	0.5338
9	0.04	2.2688	14.0827	72.772	273.5231	0.02	2	1344	0.8026
10	0.14	4.9244	30.0225	95.344	128.9586	0.22	3	581	0.9188
11	0.13	9.3386	41.0112	60.081	342.8563	0.82	4	255	0.9698
12	0.70	8.8571	11.2420	82.044	265.5420	0.85	5	108	0.9914
13	0.77	6.2865	49.7048	67.643	496.2355	3.58	6	21	0.9956
14	0.48	9.8556	39.8705	88.363	362.1178	2.15	7	16	0.9988
15	0.80	2.1258	47.0173	96.374	164.6769	0.83	8	5	0.9998
16	0.24	8.0568	12.9274	68.898	177.0998	0.36	9	1	1
17	0.86	4.4119	30.5153	71.505	120.2721	1.62	10	0	1
18	0.92	5.7683	22.1604	83.760	230.0753	1.40	11	0	1
19	0.97	6.0060	19.6878	84.097	167.2686	1.36	12	0	1
20	0.20	7.2687	41.0464	59.581	250.6831	0.99	13	0	1
21	0.38	4.9343	14.7559	60.762	265.2090	0.45	14	0	1
22	0.77	8.6882	26.9766	92.753	165.4931	1.94	15	0	1
23	0.81	8.5801	24.1947	87.065	472.8478	1.92	16	0	1
24	0.38	6.3796	19.3789	90.610	296.9762	0.52	17	0	1
25	0.02	8.4147	25.9741	70.072	366.7102	0.07	18	0	1
26	0.82	3.6672	31.8475	65.858	421.5167	1.45	19	0	1
27	0.17	8.6904	35.9404	66.909	335.0555	0.81	20	0	1
28	0.57	5.7602	31.6476	74.922	147.6830	1.39	21	0	1
29	0.78	2.7816	38.5530	92.510	217.3882	0.91	22	0	1
30	0.82	2.3118	35.5405	56.669	169.3794	1.19	23	0	1
31	0.22	4.7570	44.1715	91.617	461.5367	0.50	24	0	1

32	0.95	4.6544	48.3111	93.928	476.1782	2.27	25	0	1
33	0.13	2.9742	28.6534	52.791	478.0334	0.20	26	0	1
34	0.60	7.1636	36.2021	99.825	161.1433	1.56	27	0	1
35	0.12	2.0113	12.1731	66.765	378.5754	0.04	28	0	1
36	0.70	3.9744	11.8282	63.190	444.3195	0.52	29	0	1
37	0.28	2.8651	19.3875	76.950	482.7747	0.20	30	0	1
38	0.26	9.5333	11.0663	50.363	406.7846	0.55	31	0	1
39	0.48	2.3210	21.8669	67.517	284.3390	0.36	32	0	1
40	0.79	9.5835	12.3481	54.710	353.2730	1.70	33	0	1
41	0.41	7.0218	28.6194	68.202	108.4193	1.19	34	0	1
42	0.18	5.4867	26.7745	87.797	183.5484	0.29	35	0	1
43	0.50	5.6408	38.6187	64.206	218.1877	1.69	36	0	1
44	0.29	5.2833	12.5105	80.182	214.1955	0.24	37	0	1
45	0.34	2.5423	29.3690	71.199	405.5817	0.36	38	0	1
46	0.62	8.4168	46.3364	79.811	286.2377	3.03	39	0	1
47	0.45	8.0886	17.7650	91.712	175.7878	0.71	40	0	1



Summary Statistics

Sample Size (*N*): 10000

Central Tendency (Location)

Mean: 1.23
Median: 0.92
StErr: 0.01

Spread

StDev: 1.13
Max: 8.10
Q(.75): 1.71
Min: 0.00
Q(.25): 0.41
Range: 8.10
IQ Range: 1.30

Probability of pressure greater or Less Than

Actual EIF: 1.51
Simulated Mean: 1.23

Pr(x < 1.51) = #N/A
Pr(x > 1.51) = #N/A

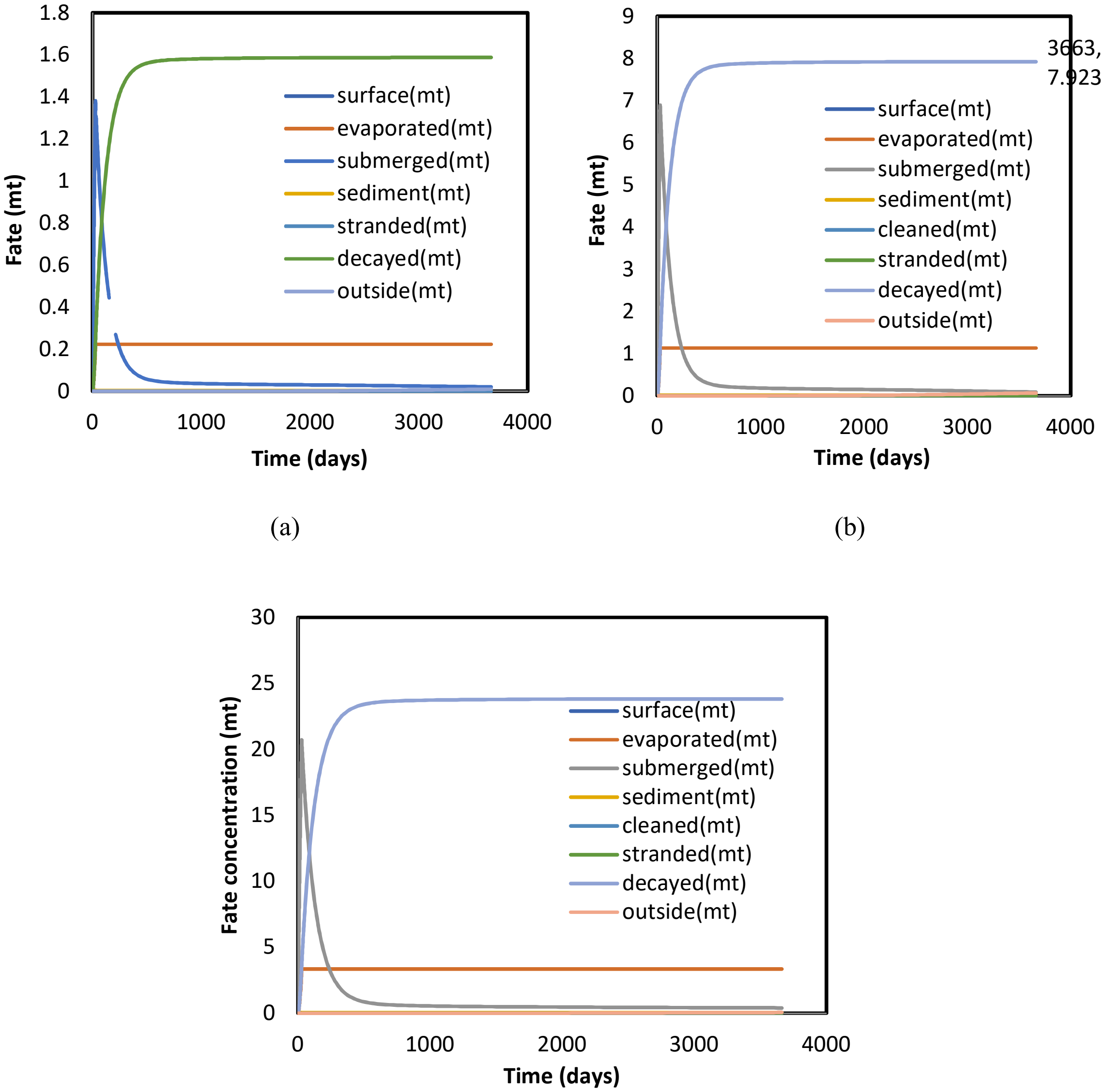
3.6. Fate of different chemical compounds

The terms used in Figure 8 are all the fate events as the fate of chemical chemicals progresses in the body of water. Surface fate is the fate event of a chemical compound that occurs on the surface of the water. Evaporated fate is the fated event of a chemical compound that is evaporated from the water's surface. Submerged fate is the fate event of the chemical compound in the body of the water column submerged. Stranded fate is the fate event of chemical compounds that are neither flowing on the surface of water nor in the water column, but are stranded in the body of the water attached to other flora and fauna ecosystems. Sediment fate is the fate event when the chemical compound settles on the surface of the sediments on the bed below the surface and column of water table. Cleaned fate is the fated event where the effect of the chemical compound is zero in the water body, the EIF has been diluted to zero.

Outside fate is the fate event of the chemical compound where the effect of the chemical compound is outside the impact zone.

Figure 8(a) shows the fate of produced water discharged for 5,000 barrels/day from the offshore platform. The fate of produced water by decay increases exponentially until it reaches 1.6 mt before it remains constant at 1.6 mt after 500 days. The submerged fate increases exponentially to 1.4 mt and decreases to zero after 500 days. Fate by evaporation is constant at 0.2 mt for all times. Fate by surface dispersion, fate by stranded pollutants and sediment fate are zero at all times. Figure 8(b) shows the fate of PW in the water column at a discharge rate of 25,000 barrels/day. The plots indicated that the profile for the simulation case of 25,000 barrels/day is nearly the same as the case for the 5000 barrels/day case, depicted in Figure 8(a). However, DREAM predicted that an increase in discharge rate from 5,000 bpd to 25,000 bpd would increase fate decay peak value from 1.6 mt to 8 mt and submerged peak value from 1.4 mt to 7 mt, and evaporation fate value from 0.2 mt to 1 mt. Figure 8(b) also shows that the decay increases exponentially with time, suggesting intake by biotic species in the water column may have deleterious effects on the environment. The increase in the fate of the water column shows the effect of PW discharges on the environment resulting from an increase in discharge rate. DREAM predicted that surface fate is zero and this may have been the result of water dilution and transport effects. The time series fate prediction is for all designated simulation sampling points located at coordinates for FS1 to FS15 falling within 50 m less than 1 km. DREAM prognosis showed that the sediment fate is zero, so, no impact of the benthic sediments should be expected for the discharged case of 25,000 bpd. Figure 8(c) shows the fate profile for PW that will be discharged from field installation for a discharge case of 75,000 bpd.

DREAM predicted that the time series fate profile by decay process is exponential. The decay may be attributed to active biotic uptake of the PW constituents. The fate by decay process peaks at a value of 24 mt in 500 days and remains relatively constant from then onwards. From Figure 8(c), at 75,000 barrels/day, DREAM predicted the impact on the water column to be 24 mt, about 15 mt times that of the 5000 barrels/day case, which has a peak of 1.6 mt. The fate due to the submerging of produced water constituents increases sharply within 28 days and is reduced to almost zero on the 100th day and beyond. This is attributed to the rapid dilution of the produced water constituents from the water surface to the water column. Equally, the fate of PW active constituents due to sediment uptake is zero. Therefore, the benthic surface may not be impacted by the PW discharge. The fate of the PW active constituents at the surface is also zero and factors of dilution may have been actively responsible for this observation. The fate evaporation is constant at 0.22 and may be responsible ultimately for the eventual reduction of produced water active constituents on the surface of the water body.



(a)

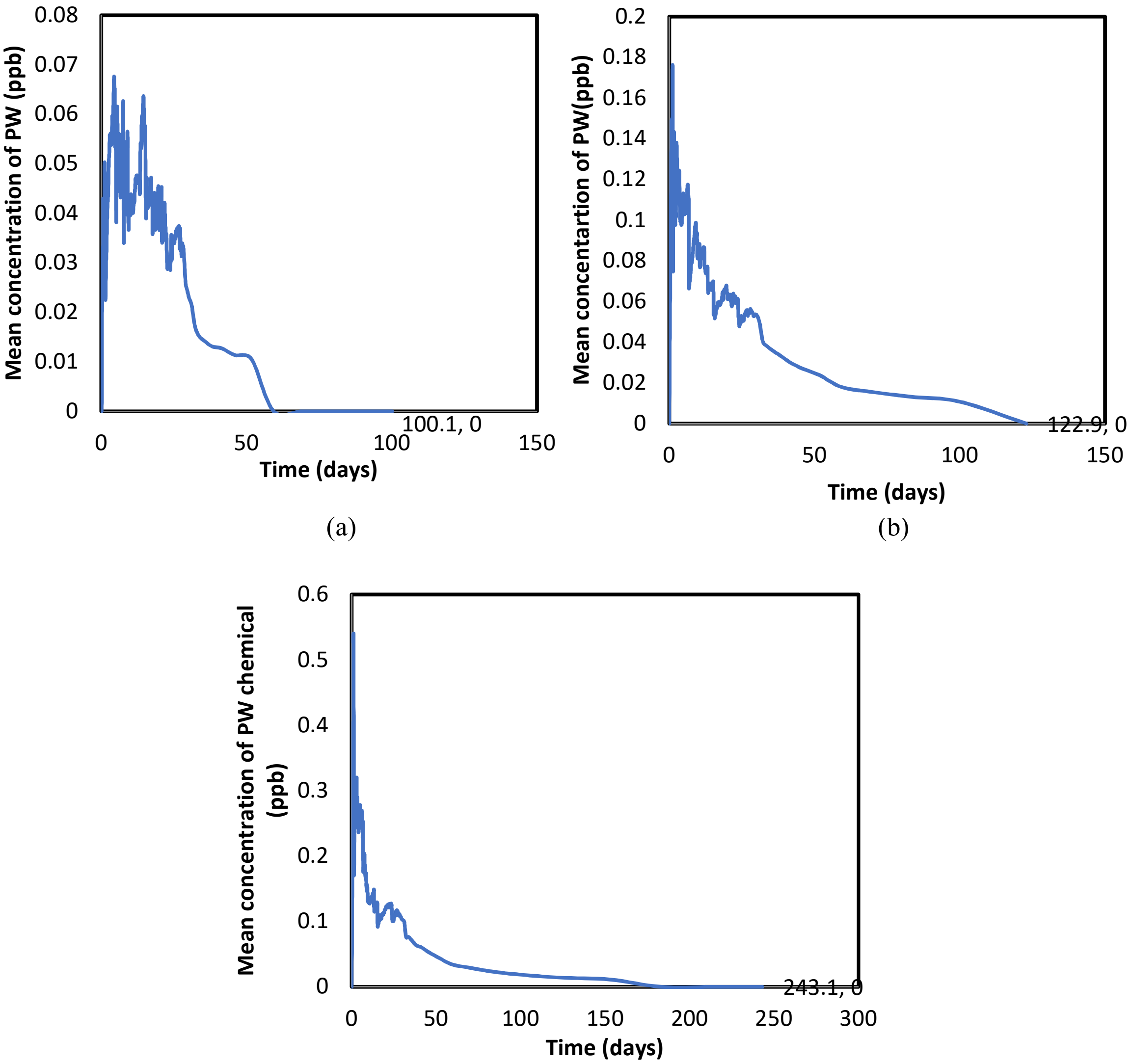
(b)

(c)

Figure 8. (a) Time series fate chart of Nigerian spatial radial grid of 1 km, (b) fate of PW on water column with time for discharge rate of 25,000 barrels/day, and (c) fate profile for PW discharged from field installation at 75,000 barrels/day.

3.7. Time Series Concentration Profiles of PW Chemical Species Within 1 km for Different Discharge Rates

Figures 9(a), 9(b) and 9(c) show the time series profile of the mean concentration of PW chemicals within 1 km at different discharge rates of 5,000, 25,000 and 75,000 barrels/day respectively. In Figure 9(a), it is observed that the PW mean concentration persists up to 50 days after the 28-day continuous discharge cycle and this is significant to draw a parallel symbiosis between PW toxicity levels, insolubility, dilution and transport by the water body. In Figure 9(b), the mean concentration peaked at 0.18 ppb in 10 days for 25,000 barrels/day discharge rate and gradually decreased to near zero after 120 days. So, it is expected that PW species persist in the water column for up to 120 days before the forces of dilution reduce the intake. In Figure 9(c), the mean concentration has a peak at 0.55 ppb in 10 days and gradually decreases to almost zero after 200 days. So, it is expected that PW chemical species should persist in the water column for up to 200 days before dilution and transport effects thereby reducing the concentration in the water column.

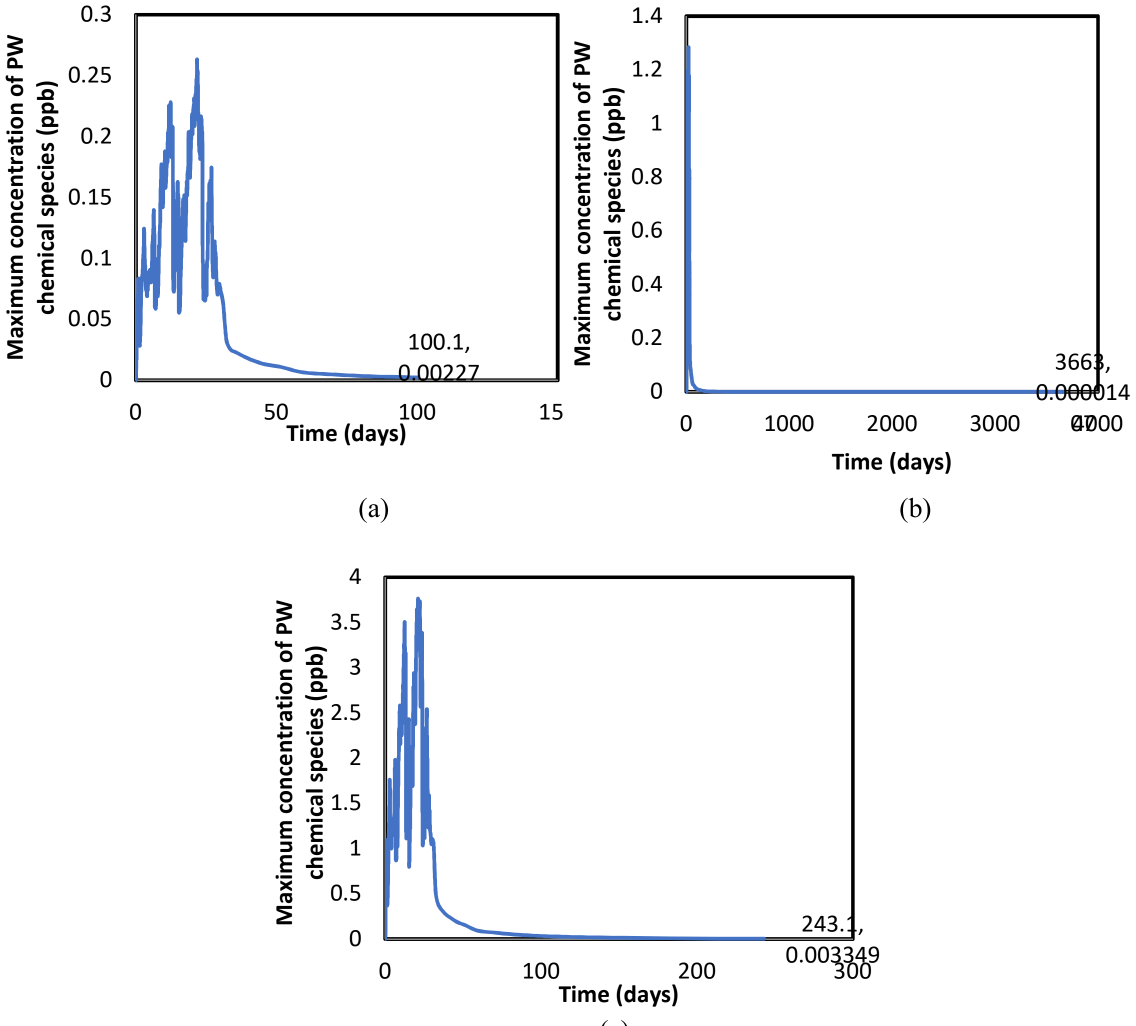


(a) (b)

(c)

Figure 9. Mean concentration of PW chemical species with time at discharge rates of: (a) 5,000 barrels/day, (b) 25,000 barrels/day, and (c) 75,000 barrels/day.

The mean concentration is the average of all the concentration values of the PW chemical species, while the maximum concentration is the largest concentration of a particular chemical species in PW. Figures 10(a), 10(b) and 10(c) show a maximum concentration of PW constituents that would be expected in the water body with respect to time at 5,000, 25,000 and 75,000 barrels/day discharge rates respectively.

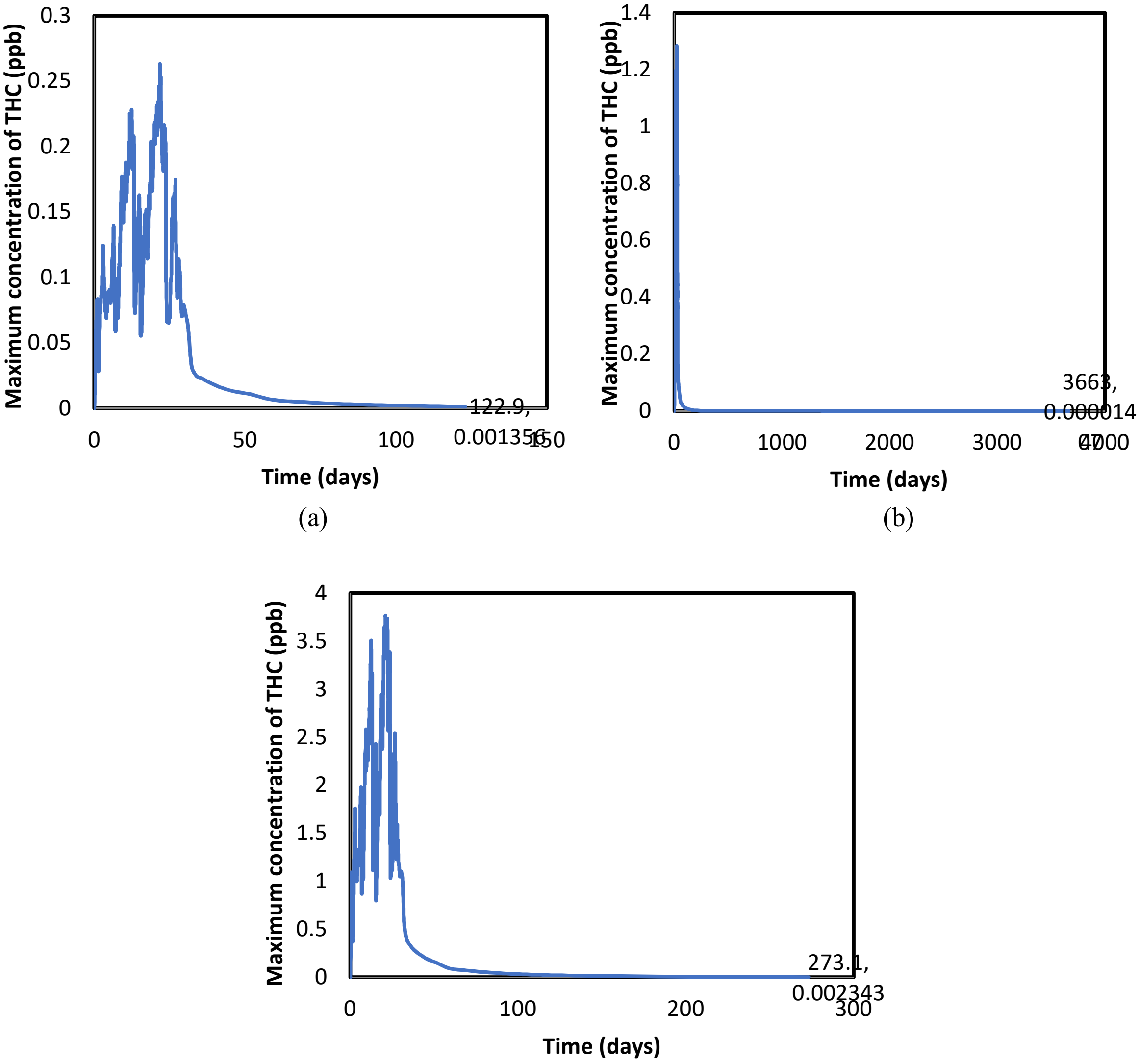


(a) (b)

(c)

Figure 10. Maximum concentration of PW chemical species with time at discharge rates of: (a) 5,000 barrels/day, (b) 25,000 barrels/day, and (c) 75,000 barrels/day.

In Figure 10(a), the predicted maximum concentration of PW chemicals increases more sinusoidally with time within 40 days and decreases exponentially to zero at the 90th day. Moreover, the difference between Figures 9(a) and 10(a) is that the maximum concentration has a peak value of 0.25 ppb with a wider span, while the mean concentration has a peak value of 0.07 ppb. From Figure 10(a), it can be observed that the maximum concentration of PW chemicals has the same profile as the predicted maximum THC. The similarity in plots reveals that the maximum PW concentration may largely be due to THC in the PW constituents. The concentration of THC in PW is 38.65 mg/L (ppm) and may be the only dominant chemical species that could persist long enough in the water column more than other PW chemical species. The model has not been used to show spatial concentration profiles but time series THC concentration up to 1 km from the point of discharge in the Nigerian field. Figures 10(b) and 11(b) are similar with an increase from zero to a peak value of 1.3 ppb from declining to almost zero within 28 days. The profile of the maximum concentration of PW chemicals and the maximum concentration of THC are the same, which is indicative of the fact that THC is the main contributor in PW constituents to the risk impact. The dilution to zero after 28 days is obvious from the plots. Figures 10(c) and 11(c) exhibit similar profiles with an increase from zero to a peak value of 1.3 ppb from where it declines to almost zero on the 100th day. The similarity of the profile shows clearly that the resultant persistence of the concentration of PW in the water body is mainly the result of the total hydrocarbon concentration (THC) only. The elongation in time of persistence of PW chemicals concentration is directly proportional to the discharge rate.



(a)

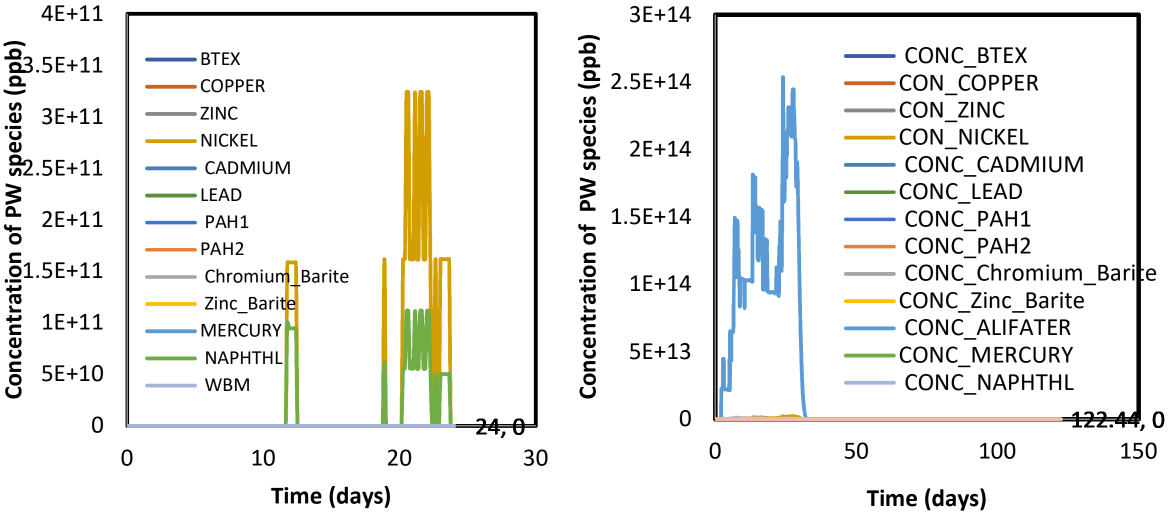
(b)

(c)

Figure 11. Time series maximum concentration of THC of PW constituents at discharge rates of: (a) 5,000 barrels/day, (b) 25,000 barrels/day, and (c) 75,000 barrels/day.

Figures 12(a) and 12(b) show the respective PW chemical species concentration with time up to 1 km radius for 25,000 and 75,000 barrels/day discharge from field installation. In Figure 12(a), DREAM predicted that significant concentrations of lead and nickel persist in the water column while the predicted nickel concentration persisted in the water column more than other PW chemicals for this

25,000 barrels/day discharge case. However, the concentration of the other chemicals in PW was negligible compared to nickel and lead. DREAM also predicted that nickel has a total concentration load of 3×10^{11} ppb, which is high compared to copper, zinc and BTEX. As shown in Figure 12(b), DREAM predicted that the time series concentration for Alifater, a dream group name for heavy hydrocarbons, is the dominant PW chemicals species exhibiting the highest concentration impact. Therefore, Alifater may persist more than the other chemicals in the water column for a discharge rate of 75,000 barrels/day. The justification for choosing a maximum width of 1 km is that simulation sampling coordinates FS1 to FS15 lie within 50 m from field installation and its impact extending up to 1 km represents the most risk that could be experienced while above 1 km radial width, the risk impact is less than the 5% margin.



(a) (b)

Figure 12. PW chemical species concentration with time at discharge rates of: (a) 25,000 barrels/day, and (b) 75,000 barrels/day.

Figure 13 shows the chart of the water column risk map of PW discharge point FS1 represented pictorially in a DREAM Bathymetry for field installation when the discharge rate is 25,000 barrels/day. From the map in Figure 13, DREAM predicted that the water column risk map for FS12 of Coordinates (Latitude 4° 05’ 57.14” N and Longitude 8° 10’ 38.06” E) would change from yellow to red, and the other fate coordinates of F11 (Latitude 4^0 06’ 03.97” and Longitude 8° 10’ 31.29” E), FS1 of coordinates (Latitude 4° 06’ 08.13” and Longitude 8° 10’ 26.69” E), and FS2-FS10, FS12, FS13, FS14 and FS15 within the impact zone would change from red to black. The black zone represents the very bad case where the EIF has reached critical thresholds. The red is a slightly moderate risk case.

Figure 14(a) shows the concentration of PW species (BTEX, copper, zinc) with time while Figure 14(b) shows PEC concentration with time for PW species (PAH1, PAH2, lead, cadmium, chromium barite, both for 25,000 barrels/day. In Figure 14(a), DREAM predicted that copper concentration has a steep sinusoidal between 20 to 25 days in the water column with a recorded peak value of 5.5×10^5 ppb. The zinc profile is, however, sinusoidal with time, which peaks at less than 1.0×10^5 ppb in 20–25 days. In Figure 14(b), the PAH2 concentration profile is a steep step sinusoidal in 20–25 days and subsequently peaked at a value of 1.2×10^6 ppb. This was closely followed by PAH1 concentration with a value of 0.1×10^6 ppb. The time series concentration values, as obtained in this study, are in consonance with the regulatory limits. The high time-series concentration values in the region of 2×10^{11} ppb are direct consequences of the high discharge rate of 25,000 barrels/day compared to the time series concentration zero values obtained for the discharge case of 3,000 barrels/day and 5,000 barrels/day.

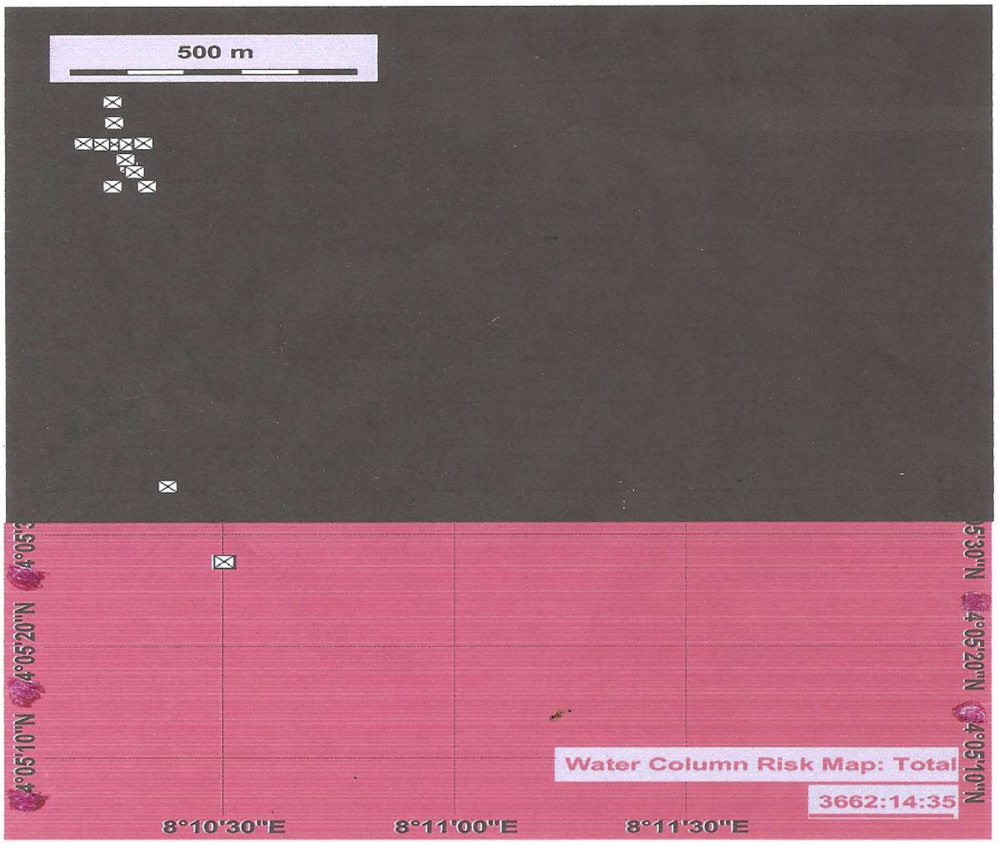
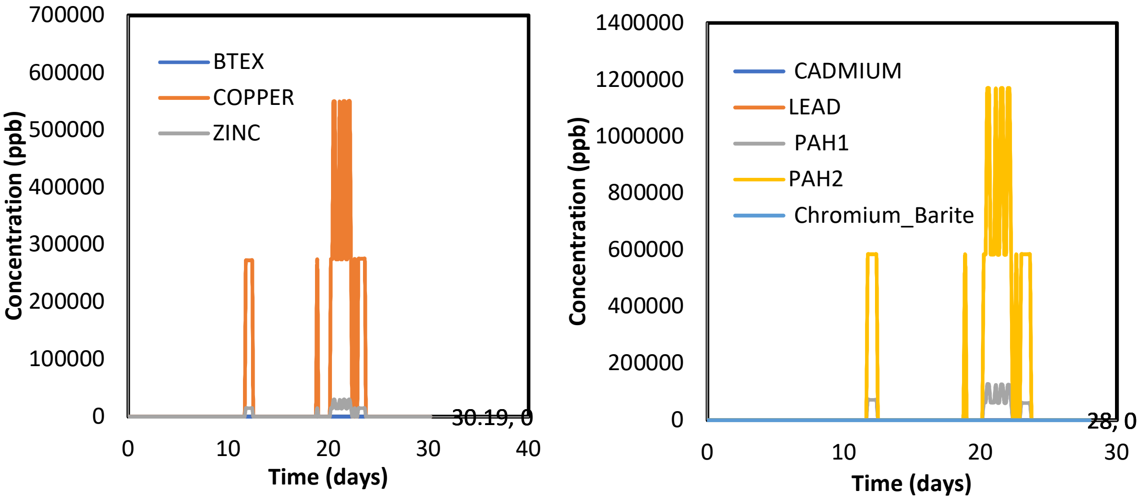


Figure 13. Chart of water column risk map for discharge case of 25,000 barrels/day.

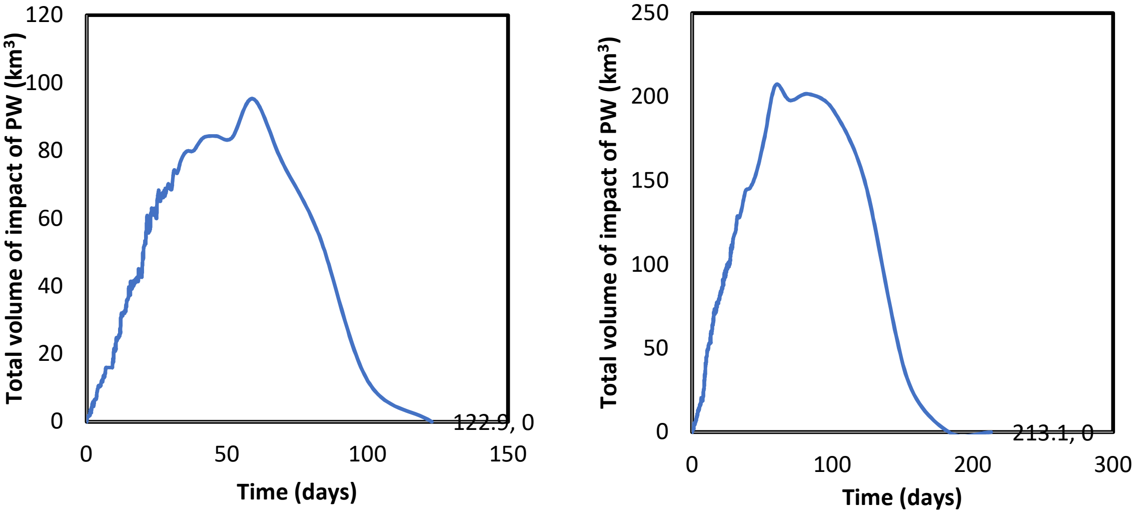
3.8. Time series profile of total volume impact for 25,000 and 75,000 barrels/day

Figures 15(a) and 15(b) show the respective total volume of the impact of PW from EBOK installation against time for 25,000 and 75,000 barrels/day. In Figure 15(a), it is observed that the impacted volume of seawater is parabolic with time as was the case for the discharge of 5,000 barrels/day where the total volume of the seawater volume impact has increased from 25 km^3 to 25 days to almost 100 km^3 in 50 days. The increase from zero to 25 km^3 during the first 60 days may be due to ocean currents dispersing PW discharge to greater volume impact. The time series impact volume reduction to zero at the 150th day as predicted by DREAM in Figure 15(a) is the combined interplay of transport and dilution by ocean currents of 3.663 m/s SE bottom, 3.08 m/s NW surface and wind speed of 6 m/s, which dispersed PW further the sea extending the impact volume grid and extending its impact. In Figure 15(b), the time series total volume impact area of PW in the sea is near parabolic, which peaked at 200 km^3 on the 75th day and exponentially decreased to zero on the 50th day and beyond. The time series impact volume reduction to zero at the 150 days is the combined interplay of transport and dilution by ocean currents of 3.663 m/s SE bottom, 3.08 m/s NW surface and wind speed of 6 m/s dispersing PW in the sea, thereby extending the impact volume grid.



(a) (b)

Figure 14. (a) Concentration of PW species (BTEX, copper, zinc) with time for discharge case of 25,000 barrels/day, and (b) PEC concentration with time for PW species (PAH1, PAH2, lead, cadmium, chromium barite) for 25,000 barrels /day.



(a) (b)

Figure 15. The total volume of the impact of PW from EBOK installation against time for (a) 25,000 barrels/day, and (b) 75,000 barrels/day.

4. Conclusions

The new model predicted that the primary contributors to EIF are copper and PAH2 compounds for designated rates of 5,000 barrels/day from field installation. Therefore, PAH2 and copper are the major risk contributors to the marine environment, where risk is well above 5%. However, for discharge rates above 5,000 barrels/day, it is observed that copper, PAH2, PAH1, zinc, nickel, cadmium, mercury and NAPHTHL seem to exceed the 5% threshold of acceptable margin. However, the model predicted that these impacts would be temporary, and were unlikely to cause cumulative impacts on sediment bottoms and surface waters after 3 days of the discharge cycle of 28 days. The produced no effect concentration (PNEC) environment baseline is a product of species toxicology, dilution factor, spread, field and metrological data, which are obtained from a regulator of the field installation. Based on the simulated data, the most suitable discharge at rates of 3,000–5,000 barrels/day produced risk within 5%. Reducing the concentration of the PAH2 and copper by chemical treatment before discharge overboard could also help to reduce the risk of EIF impact since this produced the highest EIF per chemical compound. Carrying out additional toxicity and statistical data tests could improve accuracy and discharge greater than 5,000 barrels/day should be discouraged.

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Data availability

Datasets generated or analyzed during the current study will be made available on request.

Ethical statement

The current study did not include any human or animal subjects. Thus, this study is not subject to an ethics review committee and does not require any informed consent.

Conflict of interest

We declare no conflict regarding the publication of the study.

References

[1] Lee, K. & Neff, J. (2011). Produced water: Environmental risks and advances in mitigation technologies, Springer.
[2] OSPAR (2012). Guidelines in support of recommendation 2012/5 for a risk-based approach to the management of produced water discharges from offshore installations, OSPAR Commission.

[3] OSPAR (2014). Establishment of a list of predicted no effect concentrations (PNECs) for naturally occurring substances in produced water. In: Technical Report.

[4] OSPAR (2019). Discharges, spills and emissions from offshore oil and gas installations in 2017. In: Technical Report.

[5] Beyer, J., Goksøyr, A., Hjermann, D. Ø. & Klungsøyr, J. (2020). Environmental effects of offshore produced water discharges: a review focused on the Norwegian continental shelf. *Marine Environmental Research, 162*, 105155. https://doi.org/10.1016/j.marenvres.2020.105155

[6] Nepstad, R., Hansen, B. H. & Skancke, J. (2021). North Sea produced water PAH exposure and uptake in early life stages of Atlantic cod. *Marine Environmental Research, 163*, 105203. https://doi.org/10.1016/j.marenvres.2020.105203

[7] Nepstad, R., Kotzakoulakis, K., Hansen, B. H., Nordam, T. & Carroll, J. (2023). An impact-based environmental risk assessment model toolbox for offshore produced water discharges. *Marine Pollution Bulletin, 191*, 114979. https://doi.org/10.1016/j.marpolbul.2023.114979

[8] Rye, H., Reed, M. & Ekrol, N. (1998). Sensitivity analysis and simulation of dispersed oil concentrations in the North Sea with the provann model. *Environmental Modeling Software*, *13*, 421–429. https://doi.org/10.1016/S1364-8152(98)00047-4

[9] Smit, M. G. D., Frost, T. K. & Johnsen, S. (2011). Achievements of risk-based produced water management on the Norwegian continental shelf (2002–2008). *Integrated Environmental Assessment & Management 7*, 668–677. https://doi.org/10.1002/ieam.215

[10] Ditlevsen, M.K. (2017). Eif beregninger for produsert vann fra johan castberg 2016. In: *Technical Report OC2017 F-047*.

[11] Johnsen, S., Frost, T., Hjelsvold, M. & Utvik, T. (2000). The Environmental impact factor - a proposed tool for produced water impact reduction, management and regulation. In: *SPE International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production*.

[12] Vora, M., Njau, J. G., Sanni, S. & Flage, R. (2022). Environmental risk assessment of inter-well partitioning tracer compounds shortlisted for the offshore oil and gas industry. *Energy Exploration & Exploitation 40(6)*, 1743–1759. https://doi.org/10.1177/01445987221097999

[13] McFarlane, J., Bostick, D. T. & Luo, H. (2002). Characterization and Modeling of Polluted water. *Presented at the 2002 Ground Water Protection Council Polluted Water Conference*, Colorado Springs, Co, October 16–17.

[14] Neff, J. M. (2002). Bioaccumulation in marine organisms: Effect of contaminants from oil well produced water. Amsterdam (NL): Elsevier.

[15] Nepstad, R., Nordam, T., Ellingsen, I. H., Eisenhauer, L., Litzler, E. & Kotzakoulakis, K. (2022). Impact of flow field resolution on produced water transport in Lagrangian and Eulerian models. *Marine Pollution Bulletin, 182*, 113928. https://doi.org/10.1016/j.marpolbul.2022.113928

[16] Pham, H.H.T., Lohne, H.P., Arild, Ø., Schlenk, D. & Pampanin, D.M. (2020). Modeling of Environmental Fate and Effects of Oil Leakages from Abandoned Subsea Wells Using an Environmental Impact Factor Tool. *Integrated Environmental Assessment and Management 17(3)*, 626–638. https://doi.org/10.1002/ieam.4392

[17] Ray, J.P. & Engelhardt, F.R. (1992). *Polluted Water Technological/Environmental Issues and Solutions*, Plenum Press, NY.

[18] Reed, M. & Hetland, B. (2002). DREAM: a dose-related exposure assessment model technical description of physical-chemical fates components. In: *Proceedings of SPE International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production*, Society of Petroleum Engineers.

[19] Akar, P.J. & Jirka, G. H. (1994). Buoyant spreading processes in pollutant transport and mixing, Part 1: lateral spreading in strong ambient current. *Journal of Hydraulic Research, 32*, 815–831. https://doi.org/10.1080/00221689409498692

[20] Akar, P.J. & Jirka, G.H. (1995). Buoyant spreading processes in pollutant transport and mixing, Part 2: upstream spreading in weak ambient current advection. *Journal of Hydraulic Research, 33*, 87–100. https://doi.org/10.1080/00221689409498692

[21] Doneker, R.L. & Jirka, G.H. (1990). Expert systems for hydrodynamic mixing zone analysis of conventional and toxic single port discharges (CORMIX1). *Technical Report EPA/600/3-90/012*, U.S. EPA Environmental Research Laboratory, Athens, GA.

[22] Doneker, R.L. & Jirka, G.H. (1991). Expert systems for design and mixing zone analysis of aqueous pollutant discharges. *J of Water Resources Planning and Management ASCE*, *117(6)*, 679–697. https://doi.org/10.1061/(ASCE)0733-9496(1991)117:6(679)

[23] Doneker, R.L. & Jirka, G.H. (1997). D-CORMIX continuous dredge disposal mixing zone water quality model laboratory and field validation study, OGI Technical Report.

[24] Doneker, R.L. & Jirka, G.H. (2000). The CORMIX-GI system for mixing zone prediction, regulatory analysis, and outfall design. *Marine Waste Water Disposal 2000 Conference*, Genova Italy, Nov/Dec.

[25] Doneker, R.L. & Jirka, G.H. (2001). CORMIX-GI rule-based systems for mixing zone analysis in virtual reality. *3rd International Symposium on Environmental Hydraulics*, Tempe, AZ.

[26] Doneker, R.L. & Jirka, G.H. (2001). CORMIX-GI systems for mixing zone analysis of brine wastewater disposal. *Desalination*, *139(1–3)*, 263–274. https://doi.org/10.1016/S0011-9164(01)00318-6

[27] Doneker, R.L. & Jirka, G.H. (2007). CORMIX user manual: A hydrodynamic mixing zone model and decision support system for pollutant discharges into surface waters, EPA-823-K-07-001.

[28] Jackson, L. & Myers, J. (2002). Alternative use of polluted water in aquaculture and hydroponic systems at naval petroleum reserve No. 3. *Presented at the 2002 Ground Water Protection Council Polluted water Conference*, Colorado Springs, CO, Oct. 16-17.

[29] Jirka, G.H., Doneker, R. L. & Barnwell, T. O. (1991). CORMIX: A comprehensive expert system for mixing zone analysis of aqueous pollutant discharges. *Water Science Technology, 24(6)*, 267–274.

[30] Reed, R. & Johnsen, S. (1996). Polluted water Environment Issues and Mitigation technologies, Plenum Press, New York, NY.

[31] Durell, G., Utvik, T. R., Johnsen, S., Frost, T. & Neff, J. (2006). Oil well produced water discharges to the North Sea. Part I: comparison of deployed mussels (*Mytilus edulis*), semi-permeable membrane devices, and the dream model predictions to estimate the dispersion of polycyclic aromatic hydrocarbons. *Marine Environmental Research*, *62(3)*, 194–223. https://doi.org/10.1016/j.marenvres.2006.03.013

[32] Neff, J.M., Johnson, S., Frost, T.K., Utvik, T.I.R. & Durell, G.S. (2006). Oil well polluted water discharges to the North Sea. Part II: Comparison of deployed mussels (*Mytilus edulis*) and the DREAM Model to predict ecological risk. *Marine Environmental Research*, *62*, 224-246. https://doi.org/10.1016/j.marenvres.2006.03.012

[33] Nepstad, R., Skancke, J. & Hansen, B.H. (2022). DREAM produced water plume and uptake simulations - predictions and comparisons with data from the 2021 water column monitoring at Ekofisk: plume trajectory and PAH uptake in mussels and copepods. In: Technical Report 2022:01303 A. SINTEF Ocean.

[34] Niu, H., Lee, K., Robinson, B., Cobanli, S. & Li, P. (2016). Monitoring and modeling the dispersion of produced water on the Scotian shelf. *Environmental Systems Research*, *5*, 19. https://doi.org/10.1186/s40068-016-0070-5

[35] Reed, M. & Rye, H. (2011). The DREAM model and the environmental impact factor: decision support for environmental risk management. In: Produced Water. *Springer*, 189–203.

[36] Georgie, W.J., Sell, D. & Baker, M.J. (2001). Establishing best practicable environmental option practice for polluted water management in the gas and oil production facilities. *SPE 66545, Presented at the SPE/EPA/DOE Exploration and Environmental Conference*, San Antonio.

[37] Gillibrand, P.A., Stagg, R., Turrell, W.R. & Furnes, G. (1995). Observations and modeling of the results of low-level hydrocarbons discharges in the North Sea. *ICES CM/c, 11*, 421–429.