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Simulation of oil spill trajectory on surface water with the advection-diffusion equation

A Bubu ^{1*}, YE Chad-Umoren ²

¹ Department of Physics with Electronics Technology, School of Science Laboratory Technology, University of Port Harcourt, Nigeria

² Department of Physics, University of Port Harcourt, Nigeria

* Corresponding Author: A Bubu

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Abstract

The study used the advection – diffusion equation to simulate the concentration of crude oil spilled on surface water as it disperses in the oil rich Niger Delta area of Nigeria. An assumed amount of crude oil spilled was considered which is the Idoho oil spill of 1998 of about 40,000 barrels (5440000 kg). Also varying values of distances, time, diffusion coefficient and the speed of the river were considered which is peculiar to the Niger Delta environment. The effect of distance, time, diffusion coefficient and the speed of the flowing were also discussed. These parameters have distinct effect on the concentration of oil spilled as it disperses. For a given diffusion coefficient and at a given distance, the concentration of the spill increases with time up to a certain maximum value and then begins to decrease very slowly. Also, on the effect of speed at a given diffusion coefficient and at a given distance, the concentration of the spill increases swiftly and then decreases with time.

Keywords: Advection- diffusion, oil spill, Idoho, diffusion coefficient, time, speed, distance

1. Introduction

The frequent transportation of crude in the Niger Delta area of Nigeria has been a concern for so many years. This is because of the problem that arise as a result of the dispersion of oil. During this process of movement of crude, oil spill is inevitable. Thousands of barrels of oil have been spilled into the environment through oil pipelines and tanks in the country ^[2]. This spillage may be as a result of accidental spill from tankers, routine oil tanker operations such as emptying tanks and lack of regular maintenance of the pipelines and storage tanks ^[1]. Some of these facilities have been in use for decades without replacement. The people around the coast have had experiences of an aquatic polluted environment that refuses to dry up after years of spill.

Table 1: Major spill and quantity of oil spilled, ^[2, 3]

Spills	Quantity in barrels
GOCON's Escravos spill in 1978	300,000
SPDC's Forcados Terminal tank failure in 1978	580,000
Texaco Funiwa-5 blow out in 1980	400,000
Abudu pipe line in 1982	18,818
The Idoho Oil Spill of January 1998,	40,000
SPDC Bonga spill in 2011,	40,000

According to the Department of Petroleum Resources (DPR), between 1976 and 1996 a total of 4647 incidents resulted in the spill of approximately 2,369,470 barrels of oil into the environment ^[2]. Of this quantity, an estimated 1,820,410.5 barrels (77%) were lost to the environment. A total of 549,060 barrels of oil representing 23.17% of the total oil spilt into the environment was recovered. The heaviest recorded spill so far occurred in 1979 and 1980 with a net volume of 694,117.13 barrels and 600,511.02 barrels respectively ^[2].

Available records for the period of 1976 to 1996 indicate that approximately 6%, 25%, and 69% respectively, of total oil spilled in the Niger Delta area, were in land, swamp and offshore environments. Also, between 1997 and 2001, Nigeria recorded a total number of 2,097 oil spill incidents. About 40,000 barrels of oil spilled into the environment through the offshore pipeline in Idoho [2].

Spill modeling has a long history [4]. Since 1960s, numerous oil spill models have been developed to simulate weathering processes and forecast the fate of oil spilled, in terms of providing valuable support to both contingency planners and pollution response teams [5, 6, 7]. These models, developed by various organizations, companies, and researchers, vary in complexity, applicability to location, and ease of use [8].

The advection – diffusion model is employed to effectively monitor and predict the time it would take certain quantity of crude oil dispersed to reach a particular. This will enhance oils remediation measure to be put in place.

2. Materials and Methods

Advection- Diffusion Equation

The main processes involved in the transport of oil on the water surface are advection and turbulent diffusion. Advection is mainly due to the wind, surface current and waves [9].

Let χ be the concentration of some effluent as a function of space and time. Using χ to denote effluent concentration is well established in metrological practice. Then χ is determined by the time-dependent diffusion equation which is:

$$k\nabla^2\chi = \frac{d\chi}{dt} \quad (1)$$

Or

$$\frac{kd^2\chi}{dr^2} = \frac{d\chi}{dt} \quad (2)$$

Or

$$\frac{d^2\chi}{dr^2} = \frac{1}{k} \frac{d\chi}{dt} \quad (3)$$

Where t = time in s

r = distance from the origin in km

χ = concentration of effluent in kg/m³

k = diffusion coefficient in m²/s

Fermi Age Equation

Equation (1) is identical to the Fermi age equation showing the slowing down of pollutants [10]. In solving Fermi age equation two conditions were considered: planar source in an infinite slab & planar source in an infinite medium.

Planar source in an infinite slab

Think of an infinite slab with a moderate or extrapolated thickness that is (energy-independent) and has an active planar source at its center that emits S pollutants per m²/sec energy. [11]

$$q(x, \tau) = \frac{2S}{a} \sum_{n \text{ odd}} e^{-B_n^2\tau} \cos B_n x \quad (4)$$

Equation 4 is a complete solution to the problem where $q(x, \tau)$

satisfies the age equation, the source condition, and the boundary condition at the free surface [11].

Planar Source in an infinite medium.

Using the planar source in an infinite medium solution to derive the advection - diffusion equation since it is a flowing river. The slowing density can be a function of only spatial variable and the equation is: [11].

$$\frac{d^2q(x, \tau)}{dx^2} = \frac{dq(x, \tau)}{d\tau} \quad (5)$$

Where x is measured from the center of the slab.

Using the equations

$$\frac{d^2\chi(r, t)}{dr^2} = \frac{1}{k} \frac{d\chi}{dt} \quad \text{Where } \chi \text{ is replaced with } \chi(x, r) \quad (3)$$

$$\chi(r, t) = \int_{-\infty}^{\infty} F(B, t) \cos Br dB \quad (6)$$

Where $F(B, t)$ is a function to be determined. When equ. (6) Is substituted into the differential equation (3), there is obtained [11].

$$-\int_{-\infty}^{\infty} B^2 F(B, t) \cos Br dB = \frac{1}{k} \int_{-\infty}^{\infty} \frac{\partial F(B, t)}{\partial t} \cos Br dB \quad (7)$$

It follows that $F(B, t)$ must be given by the equation

$$\frac{\partial F(B, t)}{\partial t} = -\frac{1}{k} B^2 F(B, t) \quad (8)$$

Where the general solution is

$$F(B, t) = G(B) e^{-B^2 t} \quad (9)$$

Where G (B) is a function of B. Equation (8) is a partial differential equation whose integral involves an arbitrary function instead of an arbitrary constant, as with an ordinary differential equation. Next, inserting equation (9) in equation (6) gives

$$\chi(r, t) = \frac{1}{k} \int_{-\infty}^{\infty} G(B) e^{-B^2 t} \cos Br dB \quad (10)$$

The function G(B) can be found from the source condition by placing $t = 0$ in equ. (10) thus,

$$Q\delta(r) = \frac{1}{k} \int_{-\infty}^{\infty} G(B) \cos Br dB \quad (11)$$

Where Q = amount of oil spilled

The delta function can be written in the form:

$$\delta(r) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \cos Br dB \quad (12)$$

By comparing equation (11) and equation (12) it is evident that $G(B) = Q/\sqrt{2\pi}$, so that

$$\chi(r, t) = \frac{Q}{2k\pi} \int_{-\infty}^{\infty} e^{-B^2 t} \cos Br dB \quad (13)$$

Evaluating equation (13) we have

$$\chi(r, t) = \frac{Q}{(4\pi kt)^{3/2}} e^{-r^2/4kt} \quad (14)$$

Equation (14) is, thus, the model equation for the concentration of oil spill on surface water. The equation shows the concentration of spill as a function of distance and time.

- Where Q = mass of oil injected (kg)
- k = diffusion coefficient of varying values ranging from 1.0m²/s – 2.0m²/s
- r = distance from source (km)
- t = time of dispersion (s)
- χ(r,t) = concentration of effluent (kgm⁻³)

Putting into consideration the quantity of oil spilled at the Idoho oil spill of January 1988 in Akwa Ibom state of Nigeria. The amount of oil spilled was about 40,000 barrels [2].

1 barrel = 136kg [12]
 40,000 barrels = 136kg x 40,000
 Q = 5440000kg

Effect of speed on concentration

The derivation of equation (14) is based on the assumption that the water is isotropic (invariant with respect to direction). Recall

$$\chi(r, t) = \frac{Q}{(4\pi kt)^{3/2}} e^{-r^2/4kt} \tag{15}$$

Where k is the diffusion coefficient

The water however from a flowing river is not usually stationary, there is normally a wind blowing. If this has average speed v and r coincides with the average direction of the wind, then equation. (15) can be generalized to include the wind by replacing r with r –vt.

The concentration then becomes

$$\chi(r, t) = \frac{Q}{(4\pi kt)^{3/2}} e^{-\frac{(r-vt)^2}{4kt}} \tag{16}$$

- Where Q = mass of oil injected (kg)
- k = diffusion coefficient (m²/s)
- r = distance from source (km)
- t = time of dispersion (s)
- v = average speed of water (m/s)
- χ(r,t) = concentration of effluent(kg/m³)

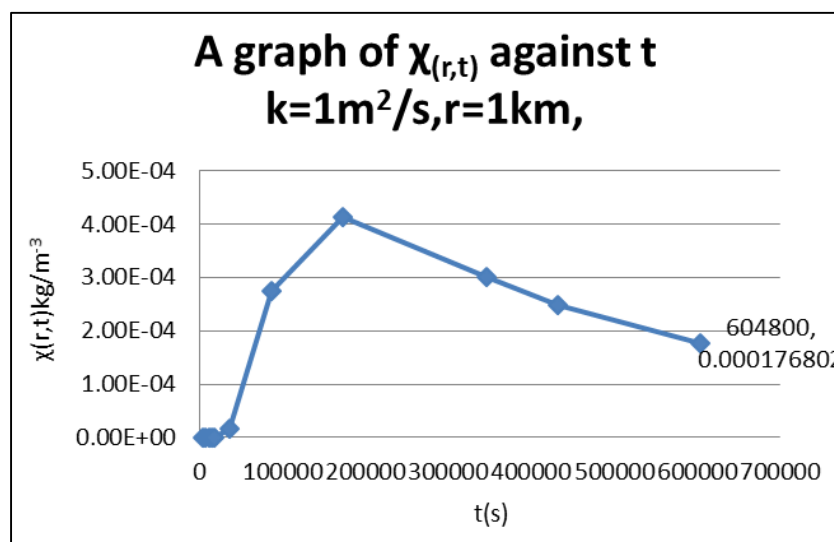
3. Results and Discussions

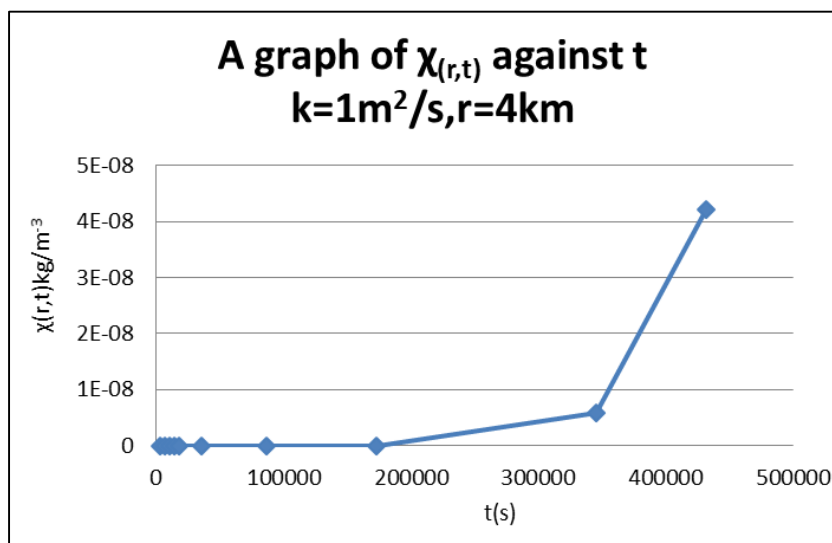
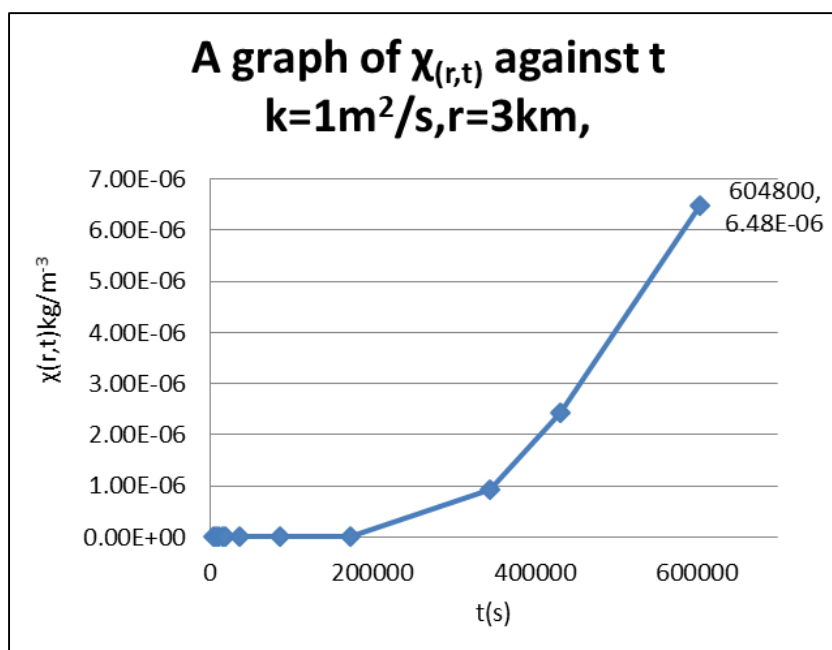
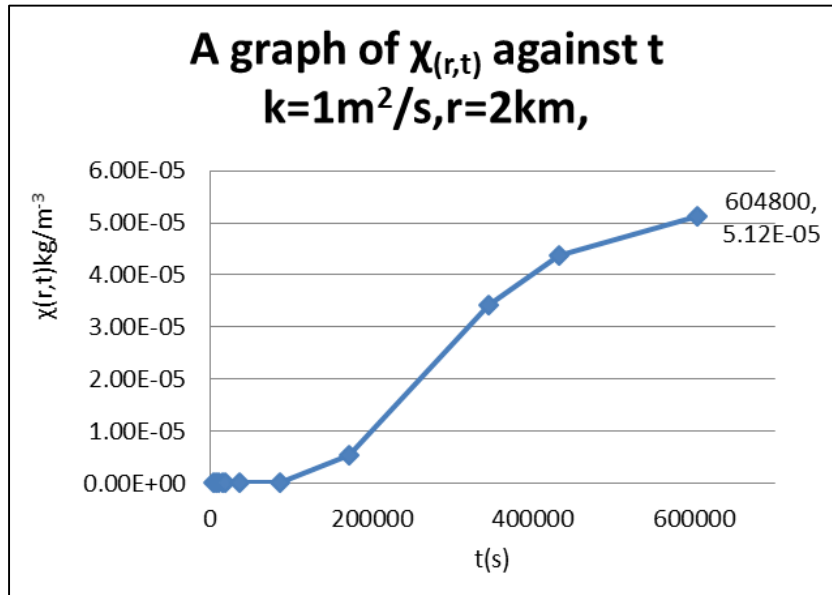
An assumed amount of spill Q which is the Idoho oil spill of about 40,000 barrels (5440000kg) was used, with varying values of diffusion coefficient k of 1.0m²/s, 1.6m²/s and 2.0m²/s, values of time t ranging from 1hr (3600s) to 7days (604800s), value of distances r of 1km, 2km, 3Km, 4Km, 5Km and 20Km and the speed of the flowing river s = 0.4m where all put into consideration.

With the above parameters, the following data and graphs were obtained:

Table 2: Variation of effluent concentration with time

k=1m ² /s, r=1km, 2Km, 3Km, 4Km, 5Km, 20Km						
t(s)	χ(r,t)kg/m ³ (r = 1km)	χ(r,t)kg/m ³ (r = 2km)	χ(r,t)kg/m ³ (r = 3km)	χ(r,t)kg/m ³ (r=4km)	χ(r,t)kg/m ³ (r=5km)	χ(r,t)kg/m ³ (r=20Km)
3600	4.03E-31	1.34E-121	2.14E-272	0	0	0
7200	1.71E-16	9.88E-62	3.95E-137	1.09E-242	0	0
10800	9.91E-12	6.87E-42	3.73E-92	1.58E-162	5.27E-253	0
14400	2.10E-09	5.04E-32	1.01E-69	1.68E-122	2.32E-190	0
18000	4.84E-08	3.88E-26	2.69E-56	1.61E-98	8.31E-153	0
36000	1.77E-05	1.59E-14	1.32E-29	1.02E-50	7.36E-78	0
86400	0.000274167	4.66E-08	2.43E-14	3.88E-23	1.90E-34	0
172800	0.000411897	5.37E-06	3.87E-09	1.55E-13	3.43E-19	8.23E-255
345600	0.000300195	3.43E-05	9.21E-07	5.82E-09	8.66E-12	1.34E-129
432000	0.000248239	4.37E-05	2.42E-06	4.22E-08	2.31E-10	1.30E-104
604800	0.000176802	5.12E-05	6.48E-06	3.5866E-07	8.69E-09	4.16E-76





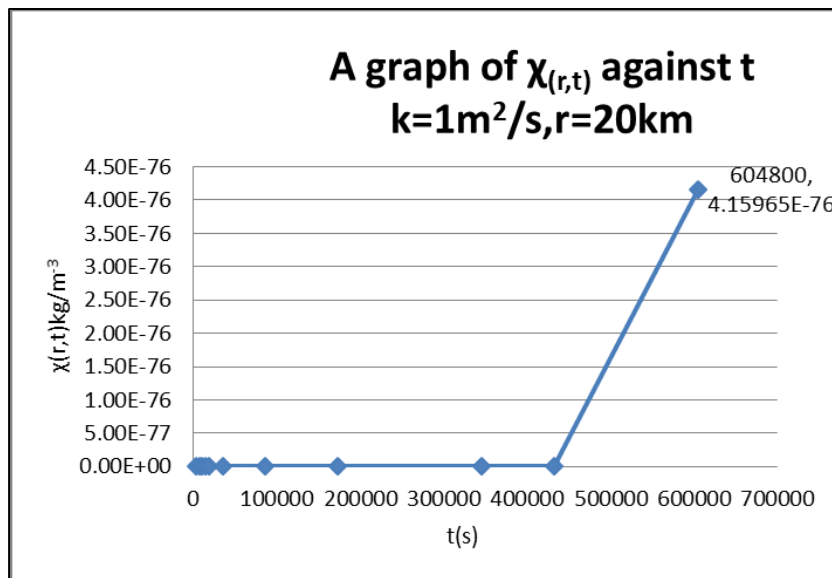
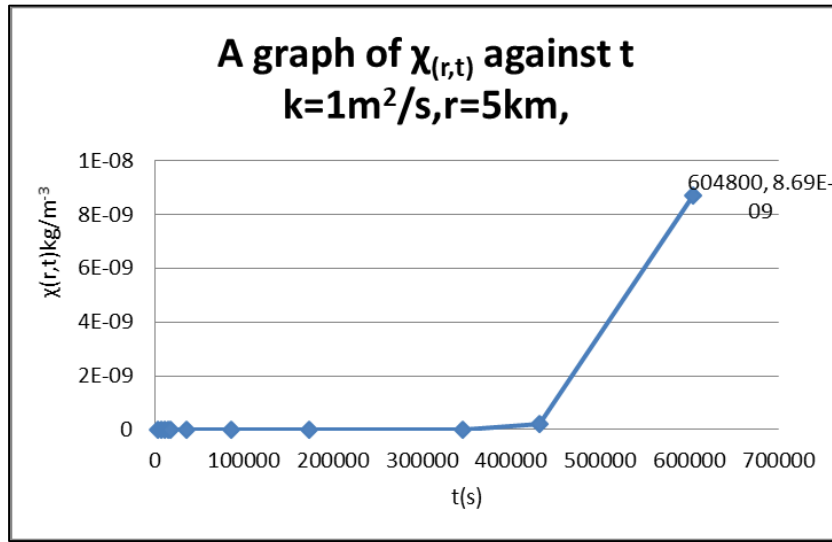
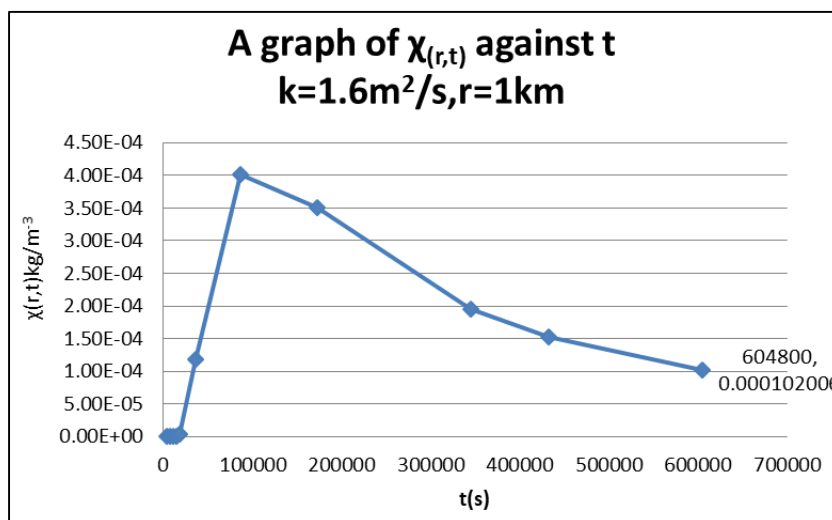
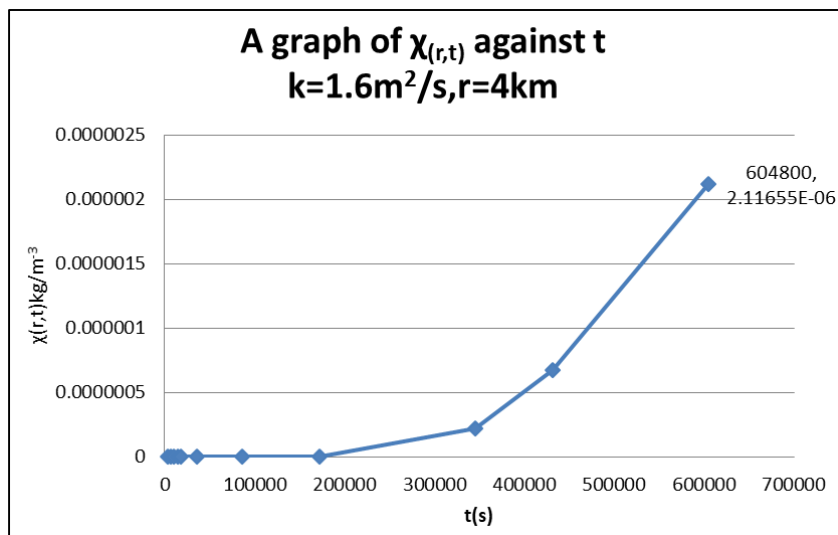
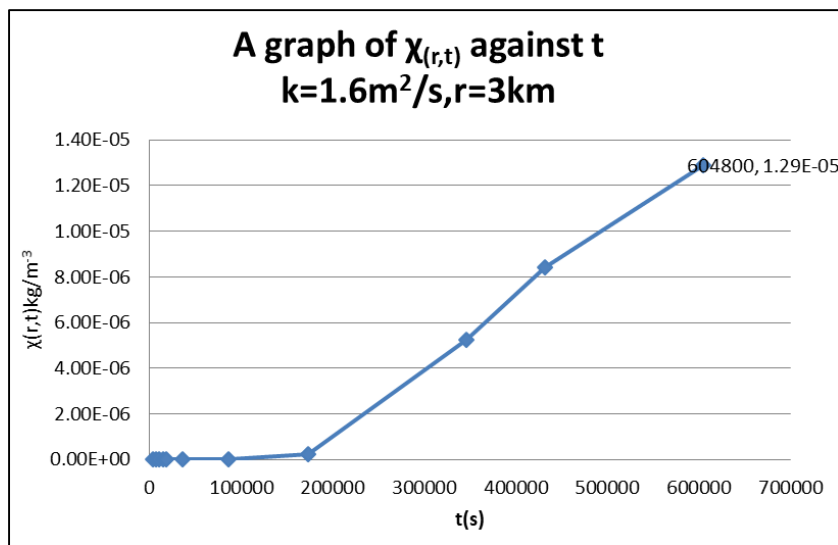
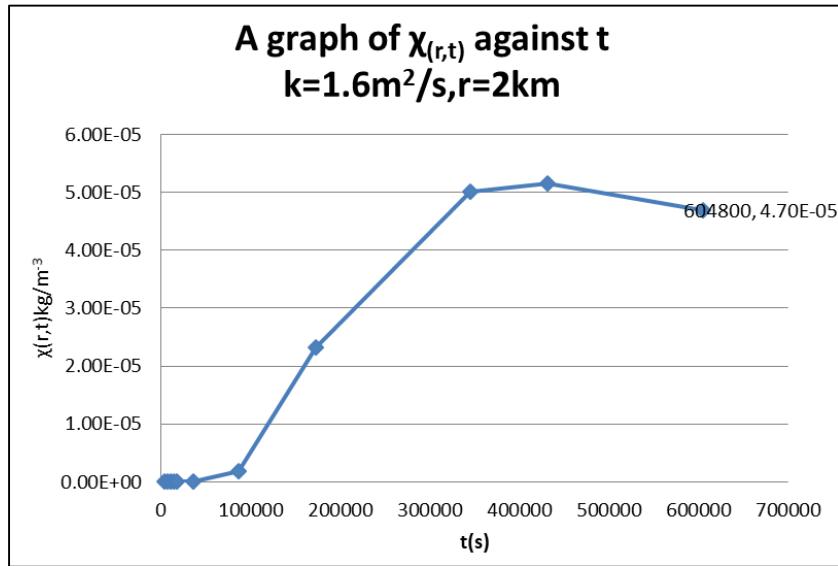


Fig 1: A graph of $\chi_{(r,t)}$ kgm⁻³ against t(s) for k=1.0m²/s at r=1Km, 2Km, 3Km, 4Km,5Km, 20Km





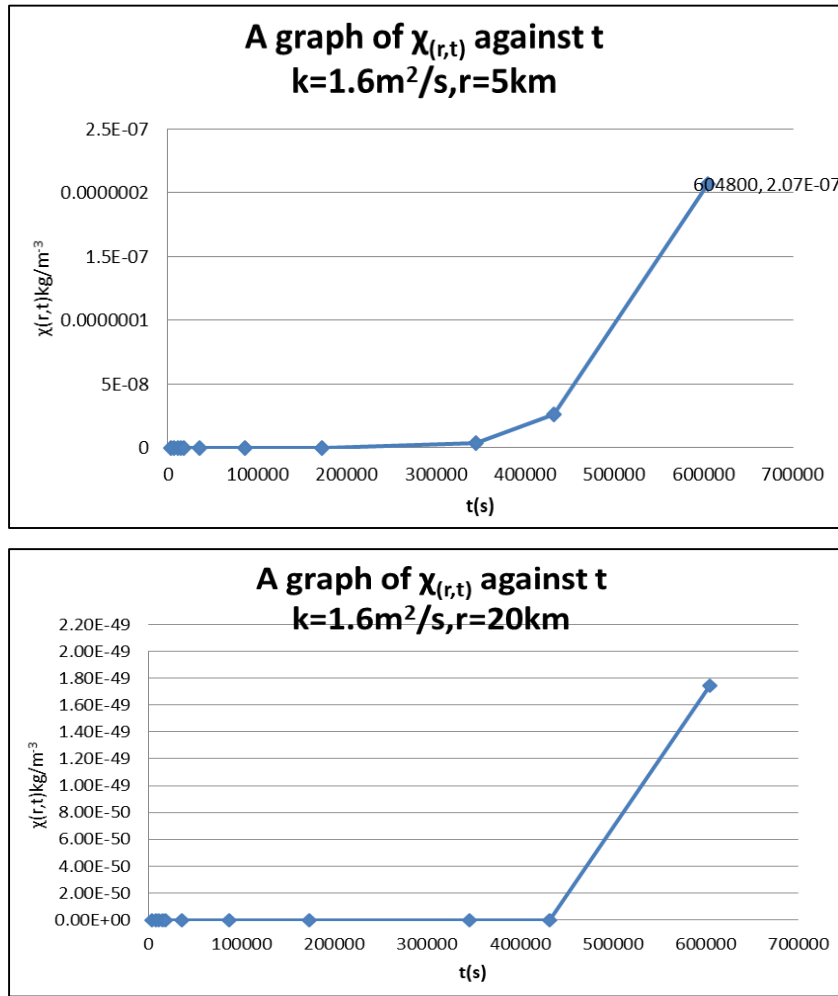


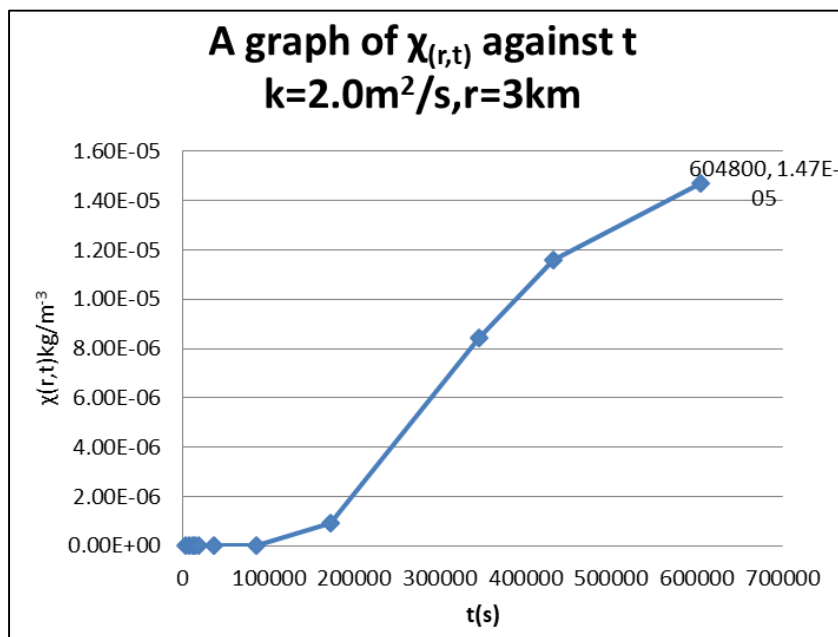
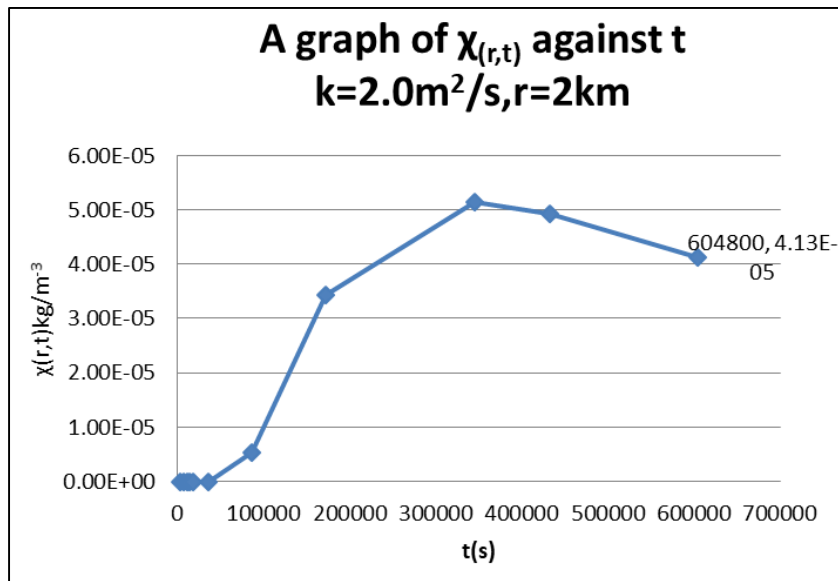
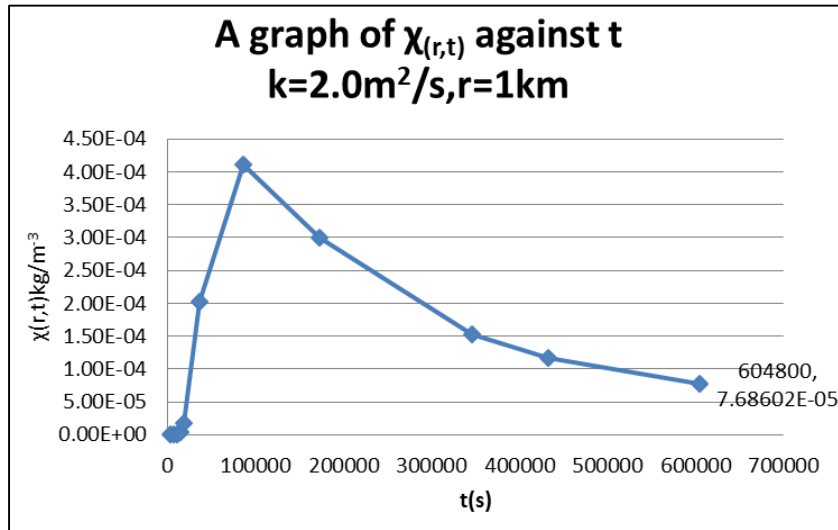
Fig 2: A graph of $\chi(r,t)$ kgm^{-3} against t (s) for $k=1.6\text{m}^2/\text{s}$ at $r=1\text{Km}, 2\text{Km}, 3\text{Km}, 4\text{Km}, 5\text{Km}, 20\text{Km}$

Table 3: Variation of effluent concentration with time

k=1.6m ² /s, r=1km, 2Km, 3Km, 4Km, 5Km, 20Km						
t(s)	$\chi(r,t)\text{kg/m}^{-3}$ (r = 1km)	$\chi(r,t)\text{kg/m}^{-3}$ (r = 2km)	$\chi(r,t)\text{kg/m}^{-3}$ (r = 3km)	$\chi(r,t)\text{kg/m}^{-3}$ (r=4km)	$\chi(r,t)\text{kg/m}^{-3}$ (r=5km)	$\chi(r,t)\text{kg/m}^{-3}$ (r=20Km)
3600	4.07E-20	1.15E-76	6.49E-171	7.335E-303	0	0
7200	3.82E-11	2.03E-39	1.53E-86	1.62E-152	2.44E-237	0
10800	2.88E-08	4.08E-27	1.56E-58	1.63E-102	4.60E-159	0
14400	6.97E-07	5.08E-21	0.00E+00	0.00E+00	5.57E-120	0
18000	4.37E-06	2.14E-17	0.00E+00	1.23E-62	1.45E-96	0
36000	1.19E-04	2.62E-10	9.87E-20	6.30E-33	6.84E-50	0
86400	0.000400935	1.77E-06	2.09E-10	6.64E-16	5.67E-23	0
172800	0.00035013	2.32E-05	2.53E-07	4.51E-10	1.32E-13	7.195E-161
345600	0.000194551	5.01E-05	5.23E-06	2.21E-07	3.77E-09	8.8194E-83
432000	0.000152384	5.15E-05	8.44E-06	6.71E-07	2.59E-08	3.2215E-67
604800	0.000102006	4.70E-05	1.29E-05	2.1165E-06	2.07E-07	1.7412E-49

Table 4: Variation of effluent concentration with time

k=2.0m ² /s, r=1km, 2Km, 3Km, 4Km, 5Km, 20Km						
t(s)	$\chi(r,t)\text{kg/m}^{-3}$ (r = 1km)	$\chi(r,t)\text{kg/m}^{-3}$ (r = 2km)	$\chi(r,t)\text{kg/m}^{-3}$ (r = 3km)	$\chi(r,t)\text{kg/m}^{-3}$ (r=4km)	$\chi(r,t)\text{kg/m}^{-3}$ (r=5km)	$\chi(r,t)\text{kg/m}^{-3}$ (r=20Km)
3600	1.71E-16	9.88E-62	3.95E-137	1.093E-242	0	0
7200	2.10E-09	5.04E-32	1.01E-69	1.68E-122	2.323E-190	0
10800	3.73E-07	3.10E-22	2.28E-47	1.49E-82	8.59E-128	0
14400	4.37E-06	2.14E-17	0.00E+00	0.00E+00	1.45E-96	0
18000	1.77E-05	1.59E-14	0.00E+00	1.02E-50	7.36E-78	0
36000	2.02E-04	6.05E-09	1.74E-16	4.85E-27	1.30E-40	0
86400	0.000411897	5.37E-06	3.87E-09	1.55E-13	3.43E-19	8.23E-255
172800	0.000300195	3.43E-05	9.21E-07	5.82E-09	8.66E-12	1.342E-129
345600	0.000152384	5.15E-05	8.44E-06	6.71E-07	2.59E-08	3.2215E-67
432000	0.000117217	4.92E-05	1.16E-05	1.53E-06	1.13E-07	8.4935E-55
604800	7.68602E-05	4.13E-05	1.47E-05	3.4618E-06	5.39E-07	1.1789E-40



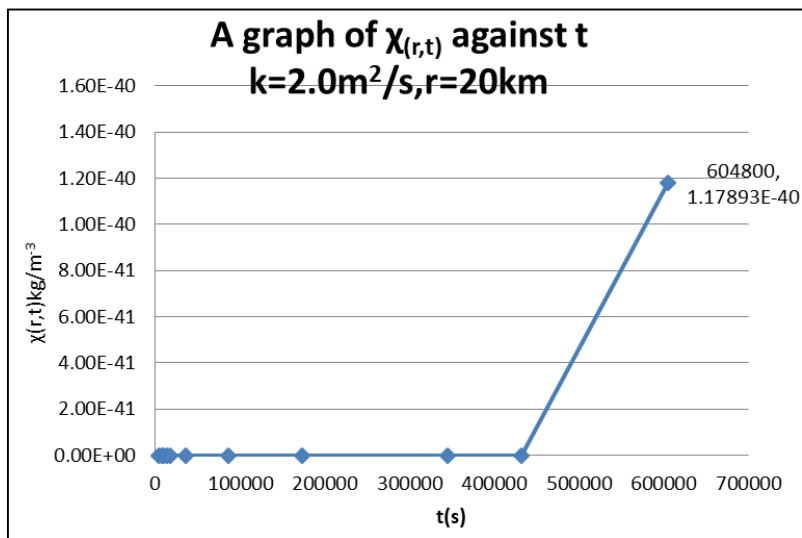
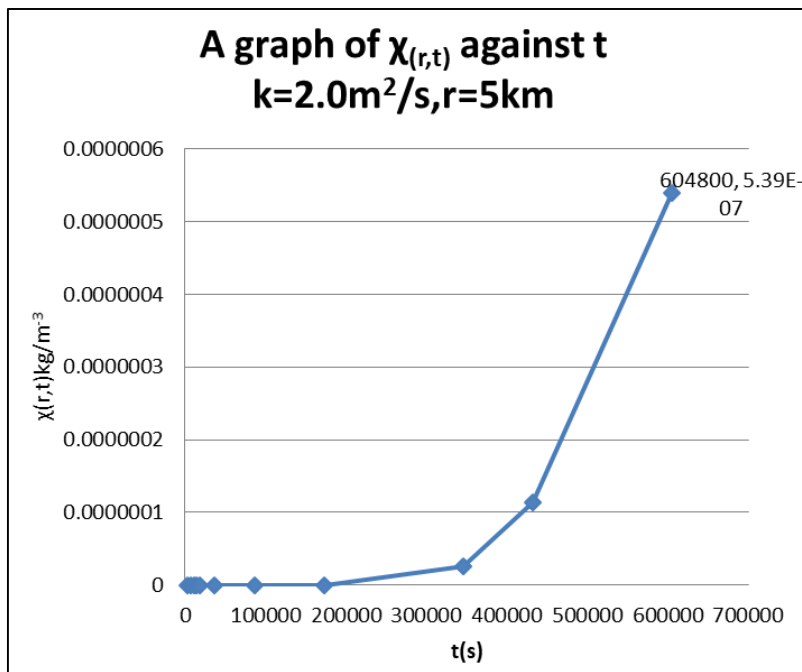
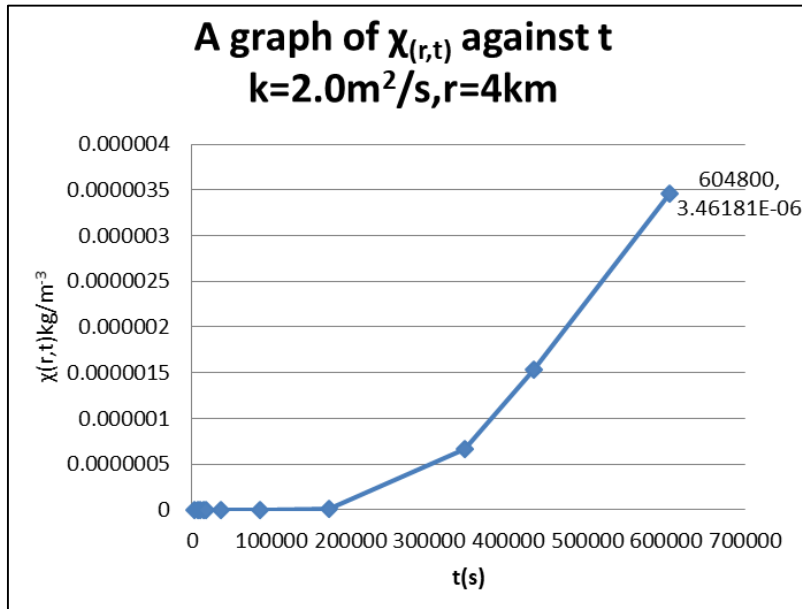


Fig 3: A graph of $\chi_{(r,t)}$ kgm⁻³ against t (s) for k=2.0m²/s at r=1Km, 2Km, 3Km, 4Km,5Km, 20K

Effect of speed on Concentration

data and graphs were obtained:

Using the average value of speed as 0.4m/s [7], the following

Table 5: Variation of effluent concentration with time

k=1.0m²/s, r=1km, 5Km, 20Km, v=0.4m/s			
t(s)	$\chi_{(r,t)}$kg/m³(r = 1km)	$\chi_{(r,t)}$kg/m³(r=5km)	$\chi_{(r,t)}$kg/m³(r = 20km)
3600	8.44E-07	0	0
7200	1.04E-54	3.46E-69	0
10800	1.74E-112	2.52E-06	0
14400	1.06E-172	3.21E-06	0
18000	7.10E-234	3.33E-31	0
36000	0	5.98E-269	4.84E-97
86400	0	0	1.97E-269
172800	0	0	0
345600	0	0	0
432000	0	0	0
604800	0	0	0

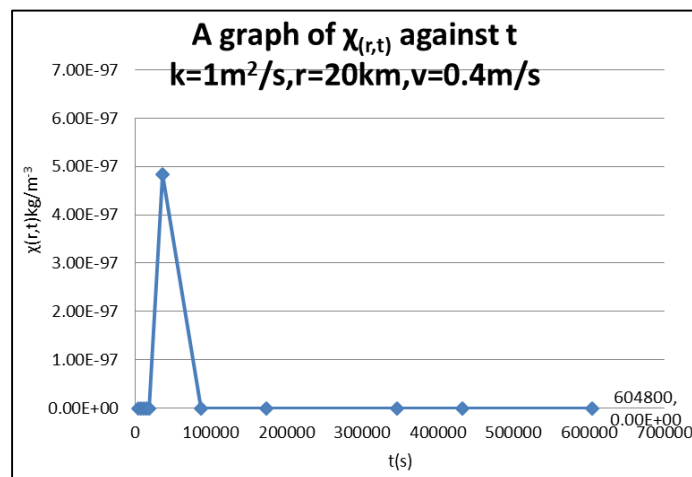
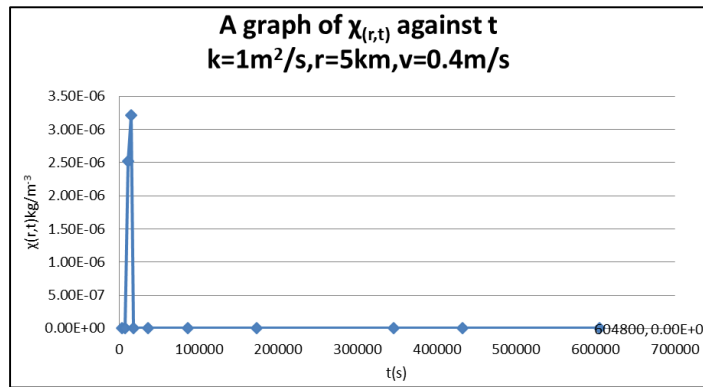
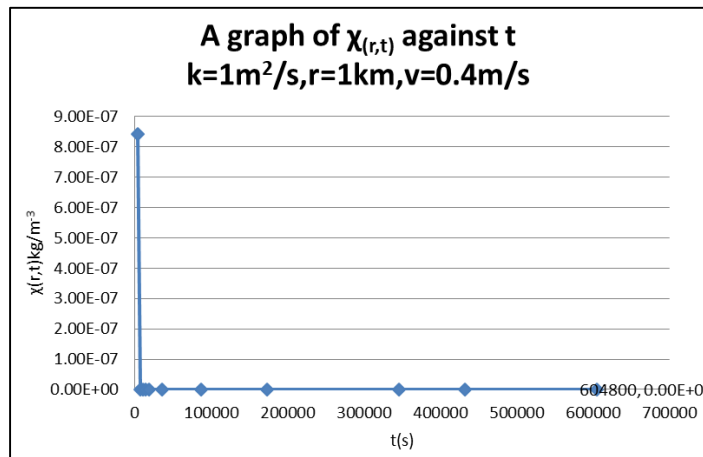


Fig 4: A graph of $\chi(r,t)$ kgm⁻³ against t (s) for k=1.0m²/s at r=1Km, 5Km, 20Km, v=0.4m/s

Table 6: Variation of effluent concentration with time

k=1.6m²/s, r=1km, 5Km, 20Km, v=0.4m/s			
t(s)	$\chi_{(r,t)}$kg/m³(r = 1km)	$\chi_{(r,t)}$kg/m³(r=5km)	$\chi_{(r,t)}$kg/m³(r = 20km)
3600	6.45E-05	3.69E-240	0
7200	4.97E-35	4.45E-44	0
10800	3.07E-71	6.88E-05	0
14400	6.08E-109	6.82E-05	0
18000	3.12E-147	1.46E-20	0
36000	0	2.53E-169	7.02E-62
86400	0	0	7.74E-170
172800	0	0	0
345600	0	0	0
432000	0	0	0
604800	0	0	0

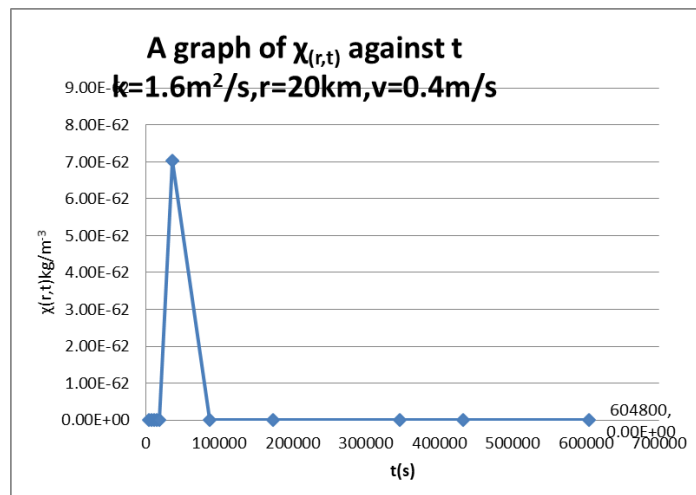
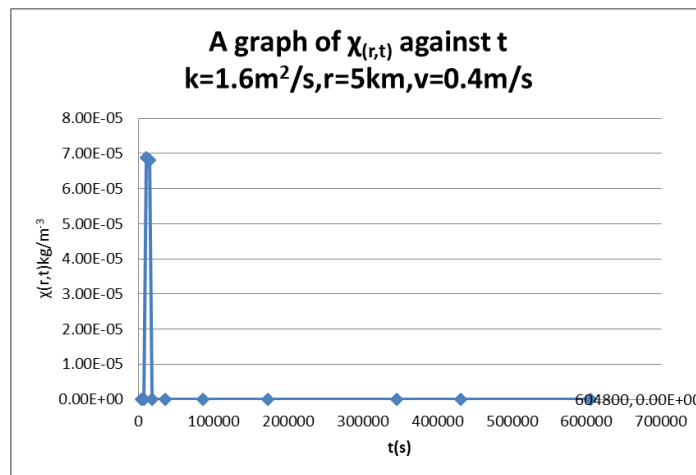
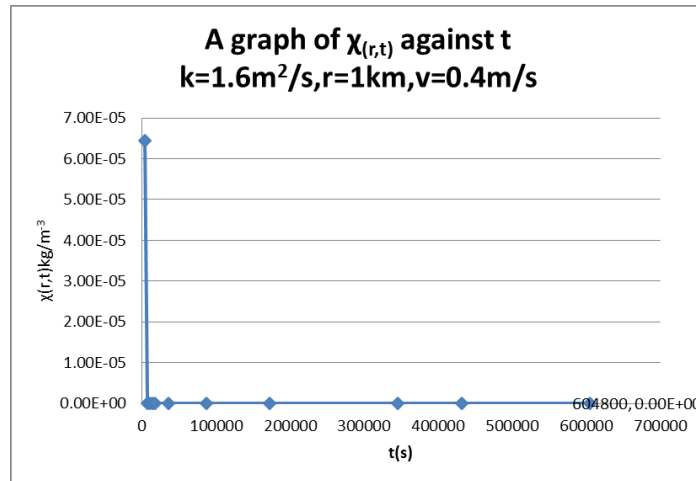


Fig 5: A graph of $\chi(r,t)$ kgm⁻³ against t (s) for k=1.6m²/s at r=1Km, 5Km, 20Km, v=0.4m/s

The data obtained from the calculation using the advection-diffusion equation shows that oil when spilled, disperses with respect to distance, diffusion coefficient, speed and time. These results agree with earlier findings by Cheng *et al.*, 2000^[13]; Li, 2001; Ventikos *et al.*, 2004^[14]; Liu and Writz, 2006^[15]; Bandyopadhyay and Chattopadhyay, 2007^[16]; Tuzkaya and Gulsun, 2008^[17], where either Eulerian or Lagrangian approaches were used. In their studies, the wind and current effect on concentration of oil spilled when it's been dispersed was considered

From the results obtained, a known quantity of oil spilled (40,000 barrels) from the source was used to calculate the concentration of the oil spilled as it disperses along its trajectory considering the effect of distance, time, speed and diffusion coefficient. Based on these, the following was observed.

Effect of Distance on Concentration

At Figure 1 when $d = 1$ km, the concentration of oil from the origin of the graph at that point (1 km) is 0 kg/m^3 . This is as a result of the spill not dispersed to that particular distance but as time goes on at that same distance 1km its concentration starts increasing up to $4.00\text{E-}04 \text{ kg/m}^3$ and decreases as it disperses. This is because the river is a flowing river in which the spilled oil disperses from that point to another point. This trend is also applicable to figures 2 and figures 3 in which the concentration of oil from the origin of the graphs at the various distances are 0 kg/m^3 followed by a slight increase and finally a decrease in concentration. In conclusion, increase in distance away from source of spill leads to slow increase in concentration of spill at various distances.

Effect of Time on Concentration

From Figures 1 to Figures 5 it can be seen that time has an effect on the concentration of the oil spilled as it disperses. Dispersion takes place with respect to time. It is observed that at a particular distance when $d = 1$ km ($k=1 \text{ m}^2/\text{s}$) the concentration starts increasing from 0 s, get to the peak and starts decreasing gradually. This trend is applicable to all the graphs. Also, the farther the distance from the source of spill the longer the time it takes for the increase in concentration. All these are as a result of the movement of the river which is not stationary. In conclusion increase in time leads to increase in concentration.

Effect of diffusion coefficient on concentration

The values of k ranging from $1.0 \text{ m}^2/\text{s}$, $1.6\text{m}^2/\text{s}$ and $2.0 \text{ m}^2/\text{s}$ were used in the advection – diffusion equation to study the concentration of spill as it disperses with the effect of diffusion coefficient. It is observed considering a particular distance where $d = 1$ km that at a lower diffusion coefficient e.g $1 \text{ m}^2/\text{s}$, the concentration at 1hr is lower than at a higher diffusion coefficient e.g $1.6 \text{ m}^2/\text{s}$ at the same time. It is applicable to all the time ask increases. Also, it is observed that figures with distance $r=1\text{Km}$ maintains a particular trend in which increase in diffusion coefficient leads to increase in concentration at a particular time and distance as can be seen from the graph.

Effect of Speed of Water Current on Concentration

The effect of speed causes an increase in the concentration from the initial time and swift decrease within a short period of time. From the graphs in Figure 4 and Figure 5, it is

observed that there is sudden increase in concentration which decays to zero within a short period of time. In conclusion, the speed of the flowing river leads to a fast decrease in the concentration of spill. Which means the dispersion of spill is fast when the speed of the river is considered.

Conclusion

A model equation which represents the concentration of oil in terms of distance and time has been developed and simulated using the advection- diffusion equation. The data and results were obtained.

From the results, it is observed that in all the graphs taking a particular distance with varying values of diffusion coefficient at a particular time, the concentration gets to its peak and decreases. This implies that increase in distance leads to decrease in concentration irrespective of diffusion coefficient.

In conclusion, the results show how well the model equation represents the concentration of oil in water as it disperses with respect to distances and time. It will also stand as an evacuation guide in case of a spill considering the distance, time and speed of dispersion of oil.

Disclaimer

There is absolutely no conflict of interest between the authors and the producers of the products because we do not intend to use these products as an avenue for any litigation but for advancement of knowledge.

Consent

It is not applicable.

Ethical Approval

It is not applicable.

Competing Interests

Authors have declared that no competing interests exist.

References

1. Nwilo CP, Badejo TO. Impacts and Management of Oil Spill Pollution along the Nigerian Coastal Areas. Administering Marine Spaces: International Issue; c2006. p. 119.
2. Jimoh A, Alhassan M. Modeling and simulation of crude oil dispersion. Leonardo Electronic Journal of Practices and Technologies. 2006;8:17-28. ISSN 1583-1078.
3. Jon Gambrell. Shell oil spill off Nigeria occurred during tank loading. Associate Press; c2011.
4. Kulygin VV. A review of modern approaches of oil spill modeling. Proceedings of the International Conference on Oil and Gas of Arctic Shelf; c2006.
5. Keramea P, Spanoudaki K, Zodiatis G, Gikas G, Sylaios G. Oil Spill Modeling: A Critical Review on Current Trends, Perspectives, and Challenges. Journal of Marine Science and Engineering. 2021;9(2):181.
6. Nelson JR, Grubestic TH. Oil spill modeling: computational tools, analytical frameworks, and emerging technologies. Progress in Physical Geography: Earth and Environment. 2019;43(1):129-143. <https://doi.org/10.1177/0309133318804977>.
7. Fingas M. Introduction to oil spill modelling. Elsevier Inc; c2017. p. 419-453. <http://dx.doi.org/10.1016/B978-0-12-809413-6.00008-4>.
8. Kubryakov A, Korataev G. A short comparison of oil spill drift forecasting systems, with an overview of the

- SEATRACKWEB system for the Moninfo Project. Commission on the Protection of the Black Sea Against Pollution. Istanbul, Turkey: Permanent Secretariat; c2010.
9. Hussein M, Jin M, Weaver JW. Development and verification of a screening model for surface spreading of petroleum. *Journal of Contaminant Hydrology*. 2002;57(3-4):281-302.
 10. Jasim MH, Muslim AG. The measurements of neutron Fermi Age for selected Nuclear Reactor shielding materials using the Indium foil technique. *Iraqi Journal of Physics*. 2013;11(22):27-3.
 11. John R. Lamarsh. *Introduction to Nuclear Reactor Theory*. Addison-Wesley Publishing Company, Reading, Massachusetts; c1966. p. 192-194.
 12. Chevron. What is in a Barrel of Oil? [Online]. 2015. Available from: http://elsegundo.chevron.com/home/aboutthrefinery/whatwedo/what_is_in_a_barrel_of_oil.aspx.
 13. Cheng NS, Law AW, Findikakis, AN. Oil transport in surfzone. *ASCE Journal of Hydraulic Engineering*. 2000;126(11):803-809.
 14. Ventikos NP, Vergitis E, Psaraftis HN, Triantafyllou G. A high-level synthesis of oil spill response equipment and Countermeasures. *Journal of Hazardous Materials*. 2004;107(1-2):51-58.
 15. Liu X, Writz KW. Consensus oriented fuzzified decision support for oil spill contingency management. *Elsevier Journal of Hazardous Materials*. 2006;134(1-3):27-35.
 16. Bandyopadhyay G, Chattopadhyay S. Single hidden layer artificial neural network models versus multiple linear regression model in forecasting the time series of total ozone. *International Journal of Environmental Science and Technology*. 2007;4(1):141-150.
 17. Tuzkaya G, Gülsün B. Evaluating centralized return centers in reverse logistics network: An integrated fuzzy multi-criteria decision approach. *International Journal of Environmental Science and Technology*. 2008;5(3):1339-1352.