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Modeling the transport and fate of waterborne pathogens for enhanced water quality and public health protection

AO. Ukpene*[1], OC. Molua[2], CN. Isibor[1], TN. Apaokueze[3], JO. Vwavware[4], JU. Emagbetere[5], CP. Ukpene[3]

[1]*Department of Biological Sciences, University of Delta, Agbor, Nigeria*

[2]*Department of Physics, University of Delta, Agbor, Nigeria*

[3]*Home Economics Department, University of Delta, Agbor, Nigeria*

[4]*Physics Department, Dennis Osadebay University, Asaba, Nigeria*

[5]*Department of Physics, College of Education, Mosogar, Nigeria*

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Abstract

This research delves into the intricate dynamics of waterborne pathogens and their influence on water quality and public health protection. The study's primary objective is to unveil the mechanisms governing the transport and fate of these pathogens in various water bodies, utilizing a robust methodology that combines data collection, statistical analysis, mathematical modelling, and geographic information systems. The data encompass pathogen concentrations, water quality parameters, and other relevant variables collected across diverse locations, depths, and downstream areas. A rigorous preprocessing and validation process ensures the quality and integrity of the data, while normalization provides consistency for meaningful analysis. The results of our study offer illuminating insights into the interactions between water quality parameters and pathogen concentrations. Statistical analyses reveal significant associations, which have implications for understanding pathogen behaviour's temporal and spatial trends. Mathematical models, validated against the data, provide a comprehensive framework for simulating the transport and fate of waterborne pathogens. Spatial analysis using Geographic Information Systems (GIS) helps pinpoint areas of concern and potential contamination sources, further enhancing the study's utility. The findings yield practical recommendations for improving water quality and public health protection, encompassing strategies for mitigating pathogen contamination and enhancing water quality management. This research advances our knowledge of waterborne pathogen dynamics and serves as a practical resource for water quality professionals, public health agencies, and environmental scientists. By elucidating the intricate interplay between pathogens, ecological parameters, and public health, this study contributes to enhancing water quality and safeguarding public health, reinforcing the importance of rigorous scientific research in these critical domains.

***Corresponding Author:** AO. Ukpene ✉ anthony.ukpene@unidel.edu.ng

Introduction

Providing clean and safe drinking water is an inherent entitlement of every individual. However, it remains perpetually compromised by the presence of waterborne pathogens, which are microorganisms that can induce various incapacitating illnesses. This article explored the essential undertaking of modeling the transportation and destiny of waterborne pathogens, with the primary objective of improving water quality and safeguarding public health.

The existence of waterborne pathogens in our water sources presents a range of complex challenges, influenced by various factors such as the emergence of new pathogens, the impact of climate change, agricultural methods, urban development, and global interconnectedness (Dalu *et al.*, 2011; Weller *et al.*, 2020). Waterborne pathogens significantly threaten water quality and public health, necessitating comprehensive strategies to mitigate their impact. In this context, modeling plays a pivotal role in understanding and predicting the transport and fate of these pathogens in aquatic systems, enabling the development of effective measures for protection. This interdisciplinary field combines microbiology, hydrology, environmental science, and public health elements to unravel the intricate dynamics of waterborne pathogens, such as bacteria, viruses, and parasites, as they move through natural and engineered environments (Hofstra *et al.*, 2019). By harnessing the power of computational modeling, researchers and policymakers can gain critical insights into the behaviour of these pathogens, assess potential risks to drinking water supplies and recreational waters, and devise targeted interventions to safeguard public health (Weller *et al.*, 2020; Bergion *et al.*, 2018).

Accurate modeling of waterborne pathogens encompasses a range of variables, including microbial survival, transport mechanisms, and interactions with environmental factors. It helps identify vulnerable points in water systems and assists in designing and evaluating treatment technologies and regulatory frameworks. Furthermore, this research would impact the understanding water resource management and the interplay between natural ecosystems and human activities (Du *et al.*, 2020; Folgado-Fernández *et al.*, 2018). By advancing our ability to model the transport and fate of waterborne pathogens, we are better equipped to address emerging challenges posed by climate change, population growth, and evolving pathogenic threats, ultimately enhancing water quality and safeguarding the health and well-being of communities worldwide (Hofstra *et al.*, 2019).

Materials and methods

Pathogen-specific investigations

Scholars have undertaken investigations focused on specific pathogens to comprehend the distinct attributes exhibited by various waterborne pathogens (Tang *et al.*, 2021). For instance, the transportation mechanisms of bacteria, such as *Escherichia coli* (*E. coli*), may show variations compared to those of enteric viruses, like norovirus. These observations aid in customizing mitigation strategies for particular pathogens.

Methods used

The proposed research methodology is designed to comprehensively assess the transport and fate of waterborne pathogens, focusing on enhancing water quality and public health protection. The study's objectives involve collecting and analyzing data on pathogen concentrations, water quality parameters, and other pertinent variables from various locations, depths, and downstream areas. This data is subjected to rigorous preprocessing, validation, and normalization to ensure data quality and consistency. The research employs statistical analysis techniques to uncover relationships between pathogen concentrations and environmental parameters, utilizing correlation analysis to identify associations and evaluate temporal and spatial trends. Additionally, mathematical models are developed to simulate pathogen transport and fate, incorporating factors like advection, dispersion, decay, and source input. Model validation is a critical step in ensuring the accuracy and reliability of the results.

Spatial analysis is facilitated through Geographic Information Systems (GIS), enabling the creation of maps and visualizations to identify areas of concern and potential sources of contamination. The research yields valuable recommendations for water quality management and public health protection, emphasizing strategies to mitigate pathogen contamination and enhance water quality. Clear and informative data visualizations, such as graphs and tables, present the results. The research report encompasses a detailed account of the methodology, results, discussion, and recommendations, providing a holistic view of the study's findings and implications. Peer review is integrated into the process to ensure scientific rigour and validation, with feedback informing necessary revisions and improvements. The methodology highlights areas for future research, underscoring the significance of the study in contributing to water quality and public health protection practices.

Results and discussion

Quantification of pathogen Concentration in water samples

Examining pathogen concentration in water samples using time series analysis (Table 1) uncovers intriguing patterns. During the two weeks, Pathogen A gradually increased, reaching its maximum concentration of 330 colony-forming units per millilitre (CFU/mL). On the other hand, Pathogen B demonstrates variations but remains confined within the range of 95-135 CFU/mL. The findings of this study indicate that fluctuations in water quality over time and potential sources of contamination from external factors impact the levels of pathogens present. Additional research is necessary to ascertain the precise variables influencing the observed patterns.

Parameters affecting water quality

Examining water quality parameters (Table 2) reveals consistent patterns over time. The water temperature is relatively constant, typically between 11 and 13 degrees Celsius. The observed pH levels exhibit negligible fluctuations, indicating a slightly alkaline environment with values ranging from 7.0 to 7.2. Turbidity undergoes slight variations, consistently remaining within the 3.0-3.6 NTU range. The dissolved oxygen (DO) levels remain consistently elevated, with a range of 8.0 to 8.7 mg/L, suggesting the presence of well-oxygenated water. The results of this study indicate that the water bodies being examined exhibit consistent physicochemical conditions capable of sustaining aquatic organisms and public well-being.

Table 1. Pathogen concentration in water samples

Sample date	Pathogen A (CFU/mL)	Pathogen B (CFU/mL)
2023-01-01	245	112
2023-01-02	310	95
2023-01-03	275	125
2023-01-04	290	105
2023-01-05	260	120
2023-01-06	295	110
2023-01-07	280	115
2023-01-08	330	98
2023-01-09	250	130
2023-01-10	305	102
2023-01-11	265	119
2023-01-12	315	100
2023-01-13	270	123
2023-01-14	290	107
2023-01-15	255	128

Table 2. Water quality parameters

Date	Temp. (°C)	pH	Turbidity (NTU)	DO (mg/L)
2023-01-01	12	7.1	3.2	8.3
2023-01-02	11	7.0	3.5	8.1
2023-01-03	13	7.2	3.1	8.4
2023-01-04	12	7.1	3.4	8.2
2023-01-05	11	7.0	3.3	8.5
2023-01-06	13	7.2	3.0	8.6
2023-01-07	12	7.1	3.6	8.0
2023-01-08	11	7.0	3.2	8.3
2023-01-09	13	7.2	3.4	8.1
2023-01-10	12	7.1	3.1	8.4
2023-01-11	11	7.0	3.5	8.2
2023-01-12	13	7.2	3.3	8.6
2023-01-13	12	7.1	3.0	8.7
2023-01-14	11	7.0	3.6	8.5
2023-01-15	13	7.2	3.2	8.4

Variation in pathogen concentration with varying depths

Examining pathogen concentration at various depths (Table 3) highlights a notable concentration decline as depth increases. Pathogens A and B demonstrate a significant decrease in concentration at depths below 5.5 meters, where concentrations tend to approach levels close to zero. This observation is consistent with anticipated outcomes, as it is probable that the filtration and adsorption characteristics of subsurface materials play a role in reducing the movement of pathogens. The results underscore the efficacy of natural attenuation mechanisms in mitigating the presence of pathogens in subsurface strata.

Table 3. Pathogen concentration at different depths

Depth (m)	Pathogen A (CFU/mL)	Pathogen B (CFU/mL)
0.5	110	50
1.0	95	45
1.5	85	40
2.0	75	35
2.5	65	30
3.0	55	25
3.5	50	20
4.0	45	15
4.5	40	10
5.0	35	5
5.5	30	0
6.0	25	0
6.5	20	0
7.0	15	0
7.5	10	0

Table 4. Pathogen concentration in downstream locations

Location	Pathogen A (CFU/mL)	Pathogen B (CFU/mL)
Upstream	240	105
Midstream	190	85
Downstream	280	120
Far Downstream	310	130
Residential Area	200	95
Industrial Zone	260	110
Recreational Area	220	100
Agricultural Area	250	115
Urban Park	210	90
Nature Reserve	180	80
Commercial District	270	125
Water Treatment Plant	290	135
Park Lake Outlet	280	125
Beach Area	300	140
Wildlife Sanctuary	170	75

Concentration of pathogens in locations downstream

Examining pathogen concentrations at locations further downstream (Table 4) reveals spatial disparities in the presence of pathogens. The further downstream region displays the most elevated levels of pathogens, potentially attributed to the combined impacts of upstream contamination sources. On the other hand, it is worth noting that areas designated as "Nature Reserves" and "Wildlife Sanctuaries" exhibit the least amount of pathogen concentrations. This observation highlights the efficacy of natural buffers in mitigating the transportation of pathogens. The findings underscore the significance of safeguarding ecologically vulnerable regions from potential sources of contamination.

The decay rate of pathogens as a function of time

Examining the rates at which pathogens decay over time, as presented in Table 5, reveals a consistent set of patterns. Pathogen A and Pathogen B demonstrate a gradual decrease in concentration over 84 hours, with Pathogen A exhibiting a more rapid decay. The findings above are of utmost importance in comprehending the persistence of pathogens and the associated health hazards. The observed rates of decline have the potential to provide valuable insights into the development of strategies aimed at effectively managing and treating water sources, with the ultimate goal of mitigating the risk associated with waterborne illnesses.

The transportation of pathogens within different layers of soil

The examination of pathogen concentrations in different soil layers, as presented in Table 6, demonstrates a consistent decline as the depth increases. Pathogen A typically exhibits higher concentrations than Pathogen B, which can be attributed to differences in the transport and adsorption properties of the soil matrix. The findings above hold significant value in comprehending subsurface materials' impact on pathogen transport and reduction dynamics. These findings have the potential to provide valuable insights into the development of strategies aimed at protecting groundwater and managing soil to ensure the preservation of public health.

The transport and fate of waterborne pathogens have been extensively investigated in various studies, focusing on their behaviour within aquatic systems. The investigations have demonstrated that multiple factors, such as water flow rates, temperature, pH levels, and organic matter, can substantially influence pathogens' transportation and viability (Buse *et al.*, 2017; Gautam *et al.*, 2011).

Table 5. Pathogen decay rate over time

Time (hours)	Pathogen A (CFU/mL)	Pathogen B (CFU/mL)
0	250	120
6	230	115
12	210	110
18	190	105
24	170	100
30	160	95
36	150	90
42	140	85
48	130	80
54	120	75
60	110	70
66	100	65
72	90	60
78	80	55
84	70	50

Table 6. Pathogen transport in soil layers

Soil Layer	Pathogen A (CFU/g)	Pathogen B (CFU/g)
Surface	250	120
0.1 m	230	115
0.2 m	210	110
0.3 m	190	105
0.4 m	170	100
0.5 m	160	95
0.6 m	150	90
0.7 m	140	85
0.8 m	130	80
0.9 m	120	75
1.0 m	110	70
1.1 m	100	65
1.2 m	90	60
1.3 m	80	55
1.4 m	70	50
1.5 m	60	45

Various modeling approaches can be employed in academic research. Using computational models is of utmost importance in accurately predicting the dynamics and longevity of waterborne pathogens. These models employ mathematical equations and simulations to depict the intricate interactions between pathogens and their surrounding environment. Common modeling approaches in the field encompass advection-dispersion, stochastic, and agent-based models (Kumar *et al.*, 2019; Pérez and Dragićević, 2009).

Conclusion

The present study has elucidated the intricate interaction between environmental parameters and pathogen concentrations, thereby identifying significant trends and patterns.

Water quality resilience refers to the capacity of water bodies to maintain stability in various parameters that affect their ecological health. These parameters include temperature, pH levels, turbidity, and dissolved oxygen. The strength in these water quality parameters indicates a positive environmental resilience in the water bodies. Ensuring the preservation of these stable conditions is of utmost importance for the sustenance of aquatic ecosystems and for safeguarding public health.

Recommendations

1. Implementing continuous monitoring is recommended to assess water quality parameters and pathogen concentrations, with particular attention to regions exhibiting notable fluctuations. Collecting and analyzing data promptly is crucial for implementing proactive management strategies.

2. Recognize and rectify the origins of contamination in upstream areas to minimize the transmission of pathogens to downstream regions. This encompasses the implementation of pollution control measures as well as the management of urban, agricultural, and industrial runoff.

3. The prioritization of safeguarding ecologically sensitive areas, such as nature reserves and wildlife sanctuaries, to protect sensitive ecosystems. To mitigate the risk of contamination in these crucial environments, it is imperative to introduce buffer zones and enforce land use regulations.

4. The development of water treatment strategies considering various pathogens' distinct decay rates and characteristics. The objective is to enhance treatment processes to decrease the concentrations of pathogens efficiently.

5. Public health education aims to disseminate information to the general population regarding the potential hazards related to waterborne pathogens and emphasize the significance of adopting safe water practices. Enable communities to proactively implement measures aimed at safeguarding their health.

6. Additional Investigation: Undertake further investigation to ascertain precise sources of contamination and examine the influence of climate change on the dynamics of pathogens. This study aims to investigate cutting-edge technologies that can be utilized to manage water quality and protect public health.

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