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Spatial Analysis and Performance Evaluation of Hospital Wastewater Treatment Plants Using GIS-Based Kernel Density Estimation and Buffer Analysis: Basrah Governorate

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ABSTRACT

Higher Hospital wastewater (HWW) poses a significant and under-regulated environmental threat in developing regions. This study aimed to evaluate the performance of hospital wastewater treatment plant (HWWTs) in Basrah governorate, Iraq, using a spatially explicit approach to address the critical gap in site-specific environmental assessment. A geospatial database was developed for seven HWWTs, and their pollutant removal efficiencies were quantified. Performance variability was analyzed using Kernel density estimation (KDE) to identify pollution hotspots and multi-distance buffer analysis(500-1500m) was employed to assess environmental risk zones. Results indicated inconsistent treatment performance, with acceptable removal for organic load (BOD/COD) but critically low efficiency for nutrients particularly phosphate (PO43-), which ranged from 20.4% to 64.1%. the spatial analysis revealed district clusters of low-performing facilities, identifying specific hospitals as significant hotspots for effluent discharge. The buffer analysis confirmed a cumulative environmental risk, with potential impacts extending to the Shatt Al-Arab River, the region's primary water source. The study concludes that the current treatment infrastructure is inadequate for the complex HWW matrix, especially concerning nutrient management. The finding validates GIS-Based spatial analysis as powerful evidence-based tool for environmental authorities to prioritize regulatory enforcement and implement site-specific management strategies in Basrah governorate.

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1. Introduction

Hospital plays a vital role in safeguarding public health by providing essential medical services and advancing clinical research. Their daily operations generate substantial quantities of hospital wastewater (HWW), which is widely recognized as one of the most critical yet underregulated sources of urban pollution. HWW complex composition includes high levels of organic matter, suspended solids, nutrients, pharmaceutical residues, antibiotic-resistant bacteria, and pathogenic microorganisms [1]. Unlike conventional municipal wastewater, hospital effluents therefore pose disproportionately high environmental and public health risks, particularly when treatment systems are insufficient, poorly maintained, or entirely absent. Under such conditions, the direct discharge of untreated or inadequately treated HWW into receiving water bodies threatens aquatic ecosystems and human health, and contributes to the dissemination of antibiotic resistance and the contamination of surface and groundwater resources [2]. The severity of this challenge is amplified by the large quantities of wastewater generated by healthcare facilities. Reported generation rates range from approximately 400 to 1200 L/day per hospital bed, with average values in developing countries often exceed those of domestic wastewater ranging from 200 – 400 L/capita/day with an average of about 750 L/day per bed, depending on hospital size and medical activity [3]. The improper management or insufficient treatment of HWW poses a severe threat to the environmental and public health risks, including contamination of surface and groundwater resources, the spread of infectious diseases and the emergence of antibiotic resistance bacteria and genes (ARGS) [2].These risks are particularly pronounced in Iraq, especially in Basrah governorate where heavy reliance on the Shatt al-Arab river coincides with escalating water pollution, salinity intrusion, and ecological degradation [4].Decades of armed conflict, upstream dam construction, seawater intrusion, and chronic water resources mismanagement have weakened the resilience of Basrah’s primary water source, rendering it highly vulnerability to industrial, agricultural and municipal pollutants [5].although existing regulations require hospital to treat their wastewater before discharge, treatment performance varies substantially among facilities, and inadequately treated effluents continue to reach nearby rivers and open channels.

Previous studies conducted in Basrah have consistently demonstrate the inadequacy of hospital wastewater treatment systems investigations of major public hospitals reported elevated concentrations of organic matter, suspended solids, salts and nutrients, largely attributed to malfunctioning, undersize or nonexistent treatment units and in some cases, the direct discharge of wastewater into surface waters [6].Dual hospital treatment plants further revealed that effluent concentrations frequently exceed Iraqi discharge or reuse standards, resulting in measurable deterioration of receiving water quality[7]. More recent assessment indicates that, although partial reductions in organic load may be achieved, overall removal efficiencies remain low due to exceptionally high influent strengths and limited treatment capacity [8,9]. While experimental and pilot-scale studies have shown that advancing biological treatment systems can significantly improve pollutant removal, their practical implementation remains limited and uneven across governorate.

At broader national and regional scales, similar challenges have been documented in other Iraqi cities and neighboring countries, where hospital wastewater is often discharged untreated into municipal sewer networks thereby increasing the burden on downstream treatment facilities [10,11] .in contrast, international treatment plants can achieve compliance with national regulations and world health organization WHO guidelines [12,13]. Collectively, the reviewed literature reveals a persistent gap between the recognized environmental risks associated with hospital wastewater and the level of treatment and monitoring currently applied in many developing regions [14,15]. Despite the growing body of research addressing the physicochemical and biological characteristics of hospital wastewater in Iraq, limited attention has been paid to its spatial variability, the identification of geographic clusters of treatment inefficiency, or the delineation of environmental influence zones surrounding hospital facilities. The absence of a cancerized geospatial database contains the capacity of environmental authorities to monitor compliance, prioritize high-risk facilities and anticipate the spatial extent of pollution impacts on surrounding land uses and sensitive receptors. This lack of especially explicit information represents a critical gap in current hospital wastewater management practices in Basrah. In this context, GIS provide powerful tools for integrating monitoring data with spatial analysis to support evidence-based environmental management. GIS-based techniques, including kernel density estimation (KDE) and buffer analysis, have been widely applied to identify pollution hotspots, analyze spatial relationships and assess environmental risk patterns that cannot captured through conventional non-spatial approaches [16,17,18]. accordingly, this study employs GIS-based spatial analysis to evaluate the performance of hospital wastewater treatment plants in Basrah governorate. The research develops a geospatial database for selected hospital treatment facilities, quantifies pollutant removal efficiencies, identifies spatial clusters of high and low performance using KDE and assesses environmental influence zone through multi-distance buffer analysis. Furthermore, the study examines spatial variation in treatment efficiency across governorate, including difference between centrally located and peripheral hospitals, and evaluates whether facilities situated within highly urbanized buffer zone (500-1500 m) pose great environmental risks. From a process perspective, the research also compares removal performance among key parameters, particularly organic load indicators (BOD and COD) versus nutrient removal nitrate (NO_3^-) and phosphate (PO_4^{3-}).

2. Methodology

i. Study Area

Basrah Governorate is located in the southern part of Iraq. It characterized by low-lying terrain and hydrological system dominated by the Shatt Al-Arab River, which represent as a primary source of water for domestic, industrial, and healthcare activities [19]. Basrah experiences significant environmental pressure due to rapid urban expansion, industrial activities, and high demand on wastewater infrastructure, particularly from institutional sources such as hospitals. The selection of Basrah Governorate as the study area is justified by its high concentration of healthcare facilities and the increasing environmental risks associated with hospital wastewater discharge. This study focuses on operational public & private hospitals within Basrah governorate that are equipped with on-site wastewater treatment units. Hospitals were selected using purposive sampling based on continuous operation during the study period, accessibility of wastewater treatment facilities and availability of influent & effluent wastewater data. Geographic coordinate of selected hospitals was collected using GPS measurement and verified through official records and satellite imagery as showing in table 1. these spatial data were integrated into a geospatial database developed using ArcGIS 10.3 software. Figure 1 presents the spatial distributions of selected hospital across Basrah governorate.

ii. Samples Selection

From 27 hospitals operating withing Basrah governorate, a purposive sample of Seven hospital was selected to this study. The selection was based on criteria designed to ensure a representative sample including :(a) geographical direction across different districts, (b) hospital type (public teaching, general, private) and (c) the presence of an operational on-site wastewater treatment plant (WWTP).

iii. Data collection and laboratory analysis

Wastewater sampling was collected from influent (raw wastewater) and effluent (treated wastewater) points of each of the selected Seven hospitals. The sampling was conducted on the same day during regular operating hours to ensure consistency and minimize temporal variability. HWW samples were collected in pre-cleaned polyethylene containers of 1-liters, preserved at approximately 4C, and transported to laboratory for analysis within 24 hours [20]. Field measurement of pH, DO, TDS were recorded on site using calibrated portable instruments. laboratory analysis was conducted to determine the physicochemical of HWW. The analyzed parameters included BOD, COD, DO, TDS, TSS, pH, NO_3^-, PO_4^{3-} and SO_4^{2-}. All analysis were performed in according with APHA [20]. Quality control procedure included instrument calibration, blank analysis and duplicate sample testing.

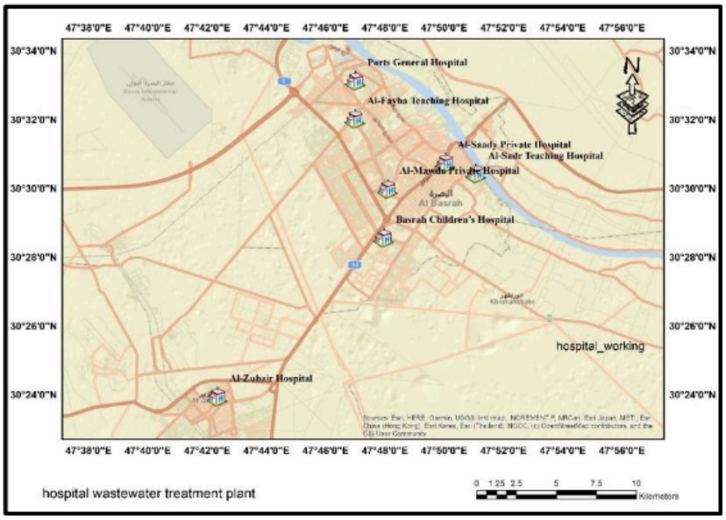

Fig. 1. Spatial Distribution of Operating Hospital Wastewater Treatment Plants in Basrah Governorate

Table 1. List of Selected Hospitals and Their Geographic Coordinates

Hospital Name	Easting(x)	Northing (y)	Treatment status	Section type
Al-Sadr Teaching Hospital	773625.4997	3378452.292	working	public
Al-Mawda Private Hospital	768862.6847	3377510.125	working	private
Ports General Hospital	766979.5096	3383273.464	working	public
Al-Zubair Hospital	759942.9793	3366105.217	working	public
Al-Fayha Teaching Hospital	767019.3593	3381220.544	working	public
Basrah Children's Hospital	768722.3149	3374872.705	working	public
Al-Saady Private Hospital	771952.0722	3378989.4	working	private

3. Data Analysis

3.1 Removal efficiency calculation

The performance of each WWTP was evaluated by calculating the Pollutant removal efficiency for each parameter except (DO, pH). The efficiency was calculated using standard formula [20, 21]:

$$Removal\ Efficiency\ (\%) = \frac{C_{in} - C_{out}}{C_{in}} \times 100$$

Where Cin and Cout represent influent and effluent concentration in (mg/L), respectively.

The calculated removal efficiency values were linked to hospital locations within GIS database to enable spatial analysis.

3.2 Geospatial analysis

All geospatial analysis were performed using ArcGIS Pro 10.3 software. A geodatabase was created contains the spatial location (coordinates) of Seven hospitals and their corresponding attribute data (influent/ effluent concentration and removal efficiencies for all parameters)

3.2.1 Inverse Distance weighting (IDW) interpolation

To create continuous spatial surfaces representing the distribution of pollutant concentration across the study area, IDW interpolation method was applied [23]. IDW is a deterministic spatial interpolation technique that estimate value at unmeasured locations based on the weighted average values from nearby measured points, with weights inversely proportional to the distance from the prediction location [24].This method was applied separately to both influent and effluent concentrations for each of the nine water quality parameters (pH, DO, TDS, TSS, BOD, COD, NO_3^-, PO_4^{3-}, SO_4^{2-}).

3.2.2. Buffer analysis

Buffer analysis was conducted to delineate zones of potential environmental influence surrounding HWW discharge points. A multi-ring buffer distance (500-1500 m) was generated to assess proximity-based environmental risk and cumulative pressure in densely populated areas. This analysis enabled identification of priority zones requiring enhanced monitoring or intervention [22].

3.2.3. Kernel Density Estimation (KDE)

To identify spatial hotspots of pollution based on effluent discharge, Kernel Density Estimation (KDE) was applied [24]. Hospital locations served as input points, while removal efficiency values were used as weighted factors. KDE is particularly effective for detecting noni-uniform spatial pattern and revealing underlying trends that may be obscured in point-based mapping [25,26]. The KDE analysis was performed specifically on the effluent concentrations of four key pollutants that pose the greatest environmental risk: COD, BOD, PO_4^{3-}, and NO_3^-. The analysis parameters were (a)Search radius: 2000 meters, (b)Output cell size: 100 meters, (c) Kernel function: Quartic. The resulting density surfaces were classified into five impact categories (Very Low Impact, Low Impact, Moderate Impact, High Impact, Severe Impact) using the Natural Breaks (Jenks).

4. Result

a. 4.1. Descriptive Analysis of Wastewater Characteristics

The analyzed parameters (pH, DO, BOD, COD, TSS, TDS, NO_3^-, $PO_4^{3-}$and SO_4^{2-}) represent the key indicators of hospital wastewater pollution. The average influent and effluent concentration for seven hospitals are summarized in Table (2 & 3), while their spatial distribution is illustrated in Appendix A (A1- A8) and appendix (B1-B8).

Table 2. Summary of Influent Water Quality Parameters (mg/L, except for pH)

Hospital Name	pH	DO	TDS	TSS	COD	BOD	NO_3^-	PO_4^{3-}	SO_4^{2-}
Al-Sadr Teaching	9.2	1.5	8436	312.6	765.5	288.4	73.3	5.4	730
Al-Mawda Private	6.9	1.4	9238	523.5	652.2	289.4	89.1	9.2	800
Ports General	6.7	0.5	5320	472.4	592.3	294.6	59.7	6.5	650
Al-Zubair	7.2	1.2	11232	298.5	892.0	398.5	71.0	7.4	550

Al-Fayha Teaching	8.1	0.8	10435	387.2	621.0	395.3	63.1	4.3	600
Basrah Children's	8.4	0.9	9540	190.7	987.2	189.9	85.6	6.0	792
Al-Saady Private	7.3	1.1	9423	169.4	878.4	387.1	97.8	8.4	520

Table 3. summary of Average effluent quality parameters (mg/L, except for pH)

Hospital Name	**pH**	**DO**	**TDS**	**TSS**	**COD**	**BOD**	**NO_3^-**	**PO_4^{3-}**	**SO_4^{2-}**
Al-Sadr Teaching	7.4	4.2	4364	54.9	159.7	56.8	16.5	4.3	360
Al-Mawda Private	7.6	4.7	4138	87.0	210.0	76.9	27.5	3.3	313
Ports General	7.9	5.4	3451	99.6	139.7	84.3	15.7	4.0	270
Al-Zubair	7.6	2.2	4344	65.3	130.0	89.9	29.0	5.6	340
Al-Fayha Teaching	9.7	1.2	5413	46.0	150.0	63.8	30.0	3.0	350
Basrah Children's	8.5	6.4	5762	47.7	264.0	65.9	33.7	3.1	332
Al-Saady Private	8.3	6.1	5341	91.3	125.0	69.7	34.6	3.6	432

Influent wastewater characteristics show substantial variability among hospitals, reflecting differences in hospital scale and wastewater generation patterns. High concentration of organic matter (COD & BOD), suspended solid (NO_3^- & PO_4^{3-}) were observed across most facilities, accompanied by low dissolved oxygen levels. Effluents concentration was generally lower than influents values; however, notable difference in treated water quality remain among hospitals. This variability indicates that HWW in Basrah governorate does not represent a uniform pollution source, supporting the need for hospital analysis rather than reliance on aggregated statistical values.

4.2 Removal Efficiency of hospital wastewater treatment plant

The removal efficiencies of BOD, COD, TSS, NO_3^- and PO_4^{3-} were calculated for each hospital and presented in table 4. To visualize the spatial patterns in treatment performance, inverse distance weighting (IDW) was applied, and the resulting spatial distributions are shown in Figures 2- 6. Removal efficiencies varied notably among hospitals and parameters. Nitrate removal ranged from 52.5% to 77.5%, while phosphate removal showed lower and more variable efficiencies (20.4-64.1%). TSS removal was generally high across most facilities, although reduced efficiency was observed at AL-SAADY private hospital. COD and BOD removal efficiencies ranged from 67.8% to 85.8% and from 65.3% to 83.9% respectively. The spatial map highlights non-uniform treatment performance across the study area, confirming clear spatial variability in pollutant removal efficiency among hospitals wastewater treatment plants.

Table 4. Calculated Pollutant Removal Efficiencies of hospital wastewater plant (%)

Hospital Name	**NO_3^-**	**PO_4^{3-}**	**TSS**	**COD**	**BOD**
Al-Sadr Teaching	77.5	20.4	82.4	79.1	80.3
Al-Mawda Private	69.1	64.1	83.4	67.8	73.4
Ports General	73.7	38.5	78.9	76.4	71.4
Al-Zubair	59.2	24.3	78.1	85.4	77.4
Al-Fayha Teaching	52.5	30.2	88.1	75.8	83.9
Basrah Children's	60.6	48.3	75.0	73.3	65.3
Al-Saady Private	64.6	57.1	46.1	85.8	82.0

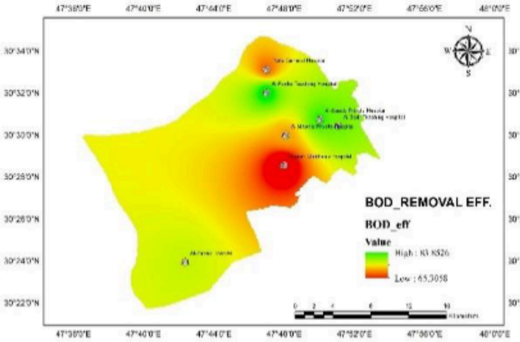

Fig 2. Spatial Distribution of BOD Removal Efficiency (%) in Hospital Wastewater Treatment Plants, Basrah

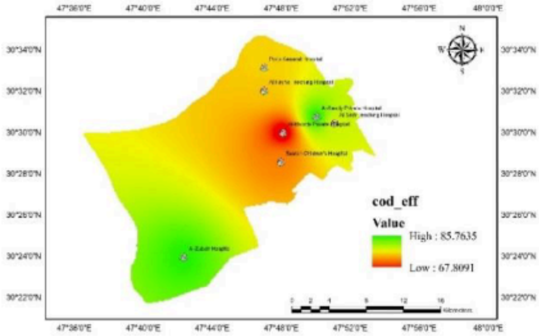

Fig 3. Spatial Distribution of COD Removal Efficiency (%) in Hospital Wastewater Treatment Plants, Basrah

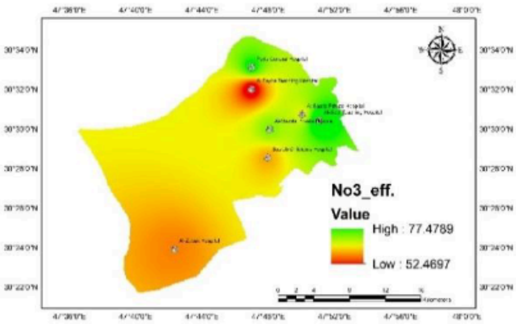

Fig 4. Spatial Distribution of NO_3^- Removal Efficiency (%) in Hospital Wastewater Treatment Plants, Basrah

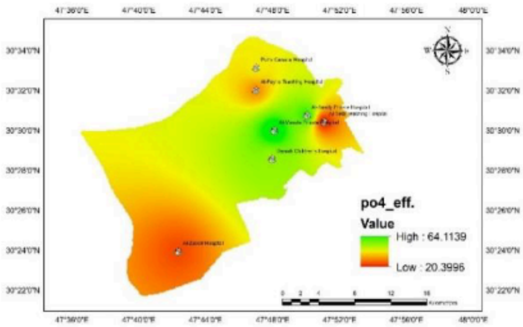

Fig 5. Spatial Distribution of PO_4^{3-} Removal Efficiency (%) in Hospital Wastewater Treatment Plants, Basrah

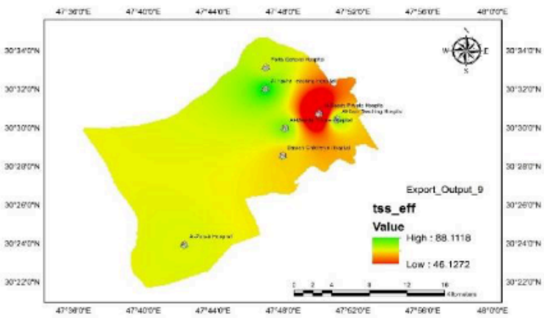

Fig 6. Spatial Distribution of TSS Removal Efficiency (%) in Hospital Wastewater Treatment Plants, Basrah

4.3 Overall Performance of Hospital Wastewater Treatment Plants

To enable an integrated assessment of HWWT performance, a composite index was developed based on the removal efficiencies of key organic and nutrient parameters (BOD, COD, TSS, TDS, NO_3^-, PO_4^{3-} and SO_4^{2-}). The index provides a unified measure of treatment efficiency, allowing direct comparison among hospitals and supporting subsequent spatial analyses. Composite index values were classified into three categories (low, moderate, high) using the natural breaks (Jenks) method, which effectively captures inherent groupings in environmental data. Figure 7. illustrates the spatial distribution of overall treatment performance across Basrah governorate. The result reveals clear spatial variability with hospitals distributed among high, moderate and low performance categories. Notably, low performance facilities exhibit spatial clustering in specific area, indicating non-uniform treatment efficiency across the governorate. This classification provides the basis for subsequent hotspot analysis using kernel density estimation and the evaluation of environmental influence zones.

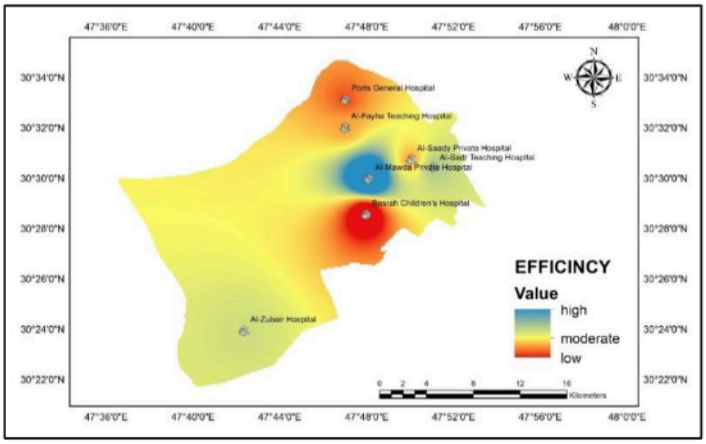

Fig. 7. Overall spatial classification of hospital wastewater treatment plant performance based on the composite index in Basrah Governorate.

4.4 Buffer Analysis of Environmental Risk Zones

The buffer zone analysis evaluates the spatial extent of potential environmental impact from hospital WWTPs in Basrah using three distances: 500m (immediate influence zone, red), 1000, (moderate impact zone, orange) and 1500 m (indirect impact zone, yellow) Figure 8. The 500 m buffer identifies areas of highest exposure, where overlapping zones in central Basrah indicate compounded risk within residential, commercial and public spaces. The 1000m buffer extends potential impact across broader urban districts through surface and drainage pathways. The 1500 m buffer represent the maximum potential dispersal, showing that cumulative hospital effluent may reach the Shatt Al-Arab River, highlighting a governorate-scale environmental risk.

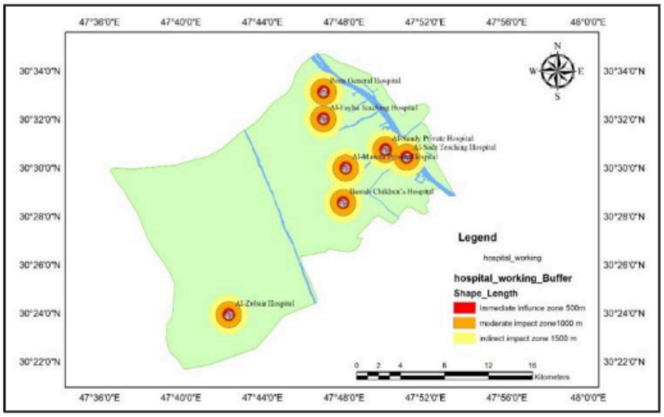

Fig. 8. Three concentric buffers around hospital WWTPs showing overlapping risk zones and proximity to the Shatt al-Arab River (blue).

4.5 Kernel Density Estimation (KDE) of Key Pollution Indicators

Kernel density estimation (KDE) was applied to the effluent concentration of COD, BOD, PO_4^{3-} and NO_3^- to identify spatial pollution hotspots (Figures 9 - 12). The results reveal distinct high-density zones indicating elevated pollution pressure. COD hotspots are concentrated around Basrah children's hospital, while BOD hotspots are observed near Al-Fayhaa teaching hospital and Al-Zubair hospital. Nutrient-related hotspots (PO_4^{3-} and NO_3^-) are primarily associated with Al-Fayhaa, Al-Mawda and Al-Zubair hospitals. These patterns demonstrate clear spatial clustering of pollution risks rather than uniform distribution across the study area.

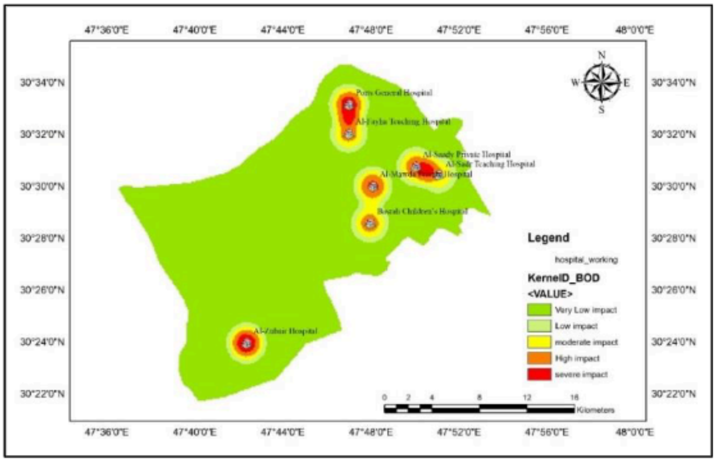

Fig. 9. Spatial Distribution of BOD Impact Using Kernel Density for Basrah Hospitals

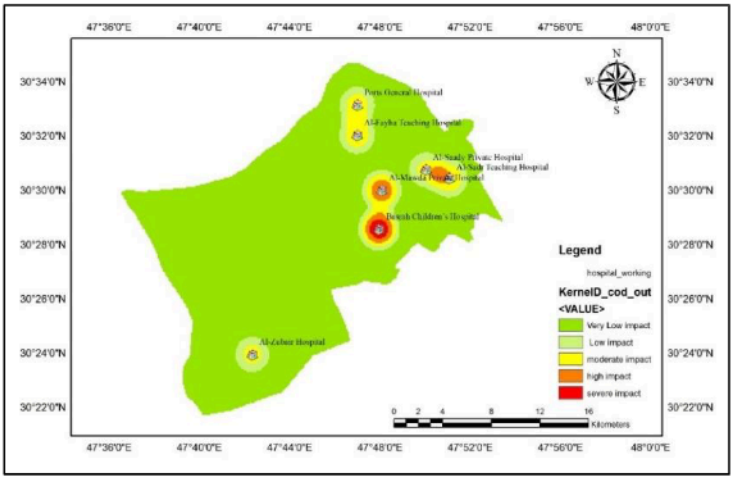

Fig. 10. Spatial Distribution of COD Impact Using Kernel Density for Basrah Hospitals

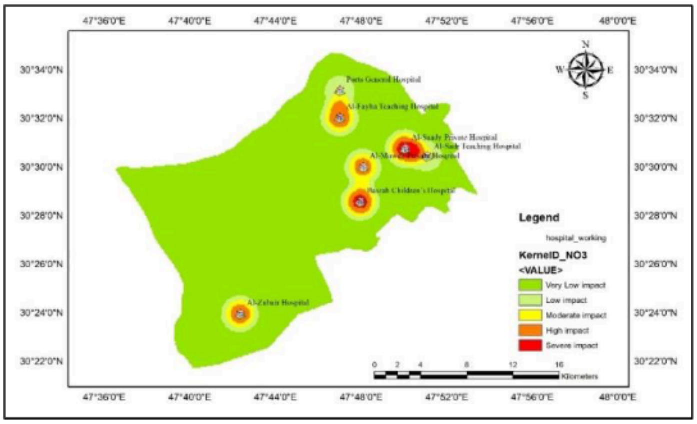

Fig. 11. Spatial Distribution of No3 Impact Using Kernel Density for Basrah Hospitals

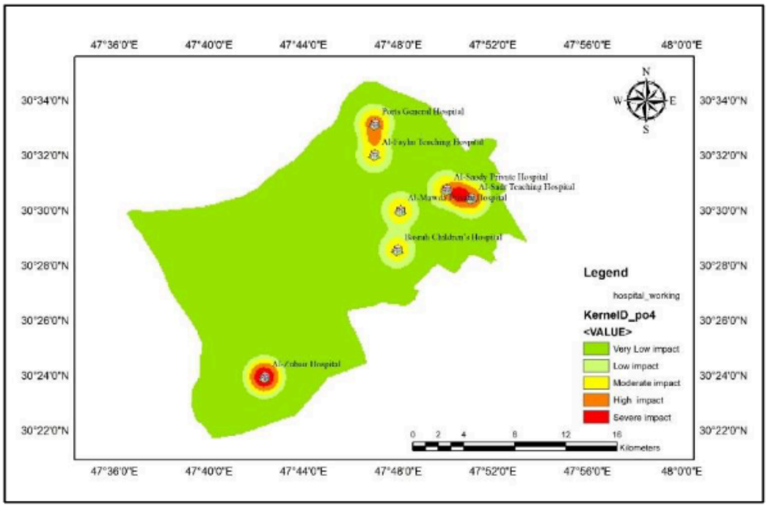

Fig. 12. Spatial Distribution of PO_4^{3-} Impact Using Kernel Density for Basrah Hospitals

5. Discussion

This spatial investigation analysis and performance assessment of HWWTs in the Basrah governorate supports the premise that there remains a disconnect between environmental risk appreciation by authorities in respect to pollution, devise policies on this, versus what level of treatment installed within the community which is consistent with review articles of previous studies [14,15]. Although an acceptable removal of organic matter-related parameters (BOD & COD) was observed with this and other hospitals' biological process, the incomplete removal of nutrients, especially phosphate (removals between 20.4% and 64.1%), reveals the incapacity of their biological treatment designs to effectively cope wastewater complex composition. This effluent is particularly high in pollutant loads, pharmaceutical residues and antibiotic-resistant bacteria [1,2]. This observed variability in performance is consistent with the findings of previous site-specific investigations [8,9] which suggested that overall treatment effectiveness is poor as a result of extremely high organic loads entering the plant and limited treatment capability. In addition, the use of geospatial methods specifically KDE and buffer analysis proved novel and was able to fill this gap as noted in the literature review; that there is no spatial assessment for assessing WWTP performance. Clear spatial agglomerations of poorly performing facilities in some areas were observed, and we suggested that certain pollution hotspots were present. It is interesting to note that some hospitals (like Basrah children's hospital) were identified among the severely impacted sites indicating that on the one hand hospital wastewater in Basrah could not be considered a homogeneous waste source.

Further, the findings of multiple-distance buffers (500–1500m) analyses, indicating the chance of cumulative effluent impact to even flow to Shatt Al Arab River are validating the environmental and public health hazards posited in earlier studies, particularly since people are highly depended on this river for drinking water [4,5]. As such, site-level, location-specific results of this type offer important empirical evidence for those charged with the responsibility to prioritize leak-risk facilities, as well as to enforce these laws/regulations designed to reduce such serious threats to the environment

5. Conclusions

Based on the comprehensive spatial analysis and performance evaluation of HWWTs in Basrah governorate, the following conclusions are drawn:

1. Inconsistent treatment performance: the HWWTs exhibit significant variability in treatment efficiency. While removal of organic load indicators (BOD and COD) is generally acceptable, the removal efficiency for nutrients, particularly phosphate (PO_4^{3-}), is critically low (ranging from 20.4% to 64.1%). This indicates that the current treatment technologies are inadequate for the complex, high-strength nature of hospital wastewater, especially concerning nutrient management.

2. Spatial Variability and Hotspots: the study successfully demonstrates that HWWT performance is not uniform across the governorate. Geospatial analysis using KDE identified distinct spatial cluster(hotspots) f low-performing facilities and high effluent concentrations for key pollutants (COD, BOD, PO_4^{3-} and NO_3^-). this finding underscores the necessity of moving beyond aggregated to a site-specific management approach.

3. Significant Environmental Risk: the multi-distance buffer analysis confirmed that the discharge from low-performing HWWTs poses a significant and cumulative environmental risk to surrounding urban areas and sensitive water bodies. The potential for effluent impact to reach the Shatt al-Arab river, the region's primary water source, highlights a critical public health and ecological threat.

4. Validation of Geospatial Tools: the research validated the utility of GIS-Based spatial analysis (KDE & Buffer analysis) as powerful, evidence- based tool for environmental authorities to monitor compliance, prioritize high-risk facilities and inform strategic planning for hospital wastewater management in developing regions.

6. Recommendations

Based on the finding and conclusions of this study, the following recommendations are proposed for environmental authorities and hospital management in Basrah governorate:

1.Technological Upgrade for Nutrient Removal: hospital administrations must prioritize the upgrade of existing WWTPs to incorporate advanced biological treatment processes capable of effective nitrification and denitrification to significantly enhance the removal of nitrogen and phosphorus compounds.

2. Spatially-explicit Monitoring and Regulation: environmental regulatory bodies should implement a spatially-explicit monitoring program that focuses on identified pollution hotspots (e.g. AL-Fayha, AL-Zubair and Basrah children's hospitals). Regulatory compliance must be strictly enforced, especially for nutrient discharge limits.

3. Risk-based Planning: future permitting and expansion of HWWTs should adopted a risk-based planning approach that incorporate buffer analysis results, giving higher scrutiny to facilities located within the 500m and 1000m influence zones for sensitive receptors.

4.Centralized Geospatial Database: the environmental directorate should establish a centralized geospatial database containing the performance data and spatial coordinates of all HWWTs to facilitate continuous data-driven assessment and rapid intervention.

7. References

[1] Majumder A., Gupta A. K. , Ghosal P. S., Varma M. (2020). A review on hospital wastewater treatment: A special emphasis on occurrence and removal of pharmaceutically active compounds, resistant microorganisms, and SARS-CoV-2. Journal of Environ. Chem. Eng. 2020 Nov 22;9(2):104812. **https://doi.org/10.1016/j.jece.2020.104812**

[2] Zhang X., Yan S., Chen J., Tyagi R. D., & Li J. (2020). Physical, chemical, and biological impact (hazard) of hospital wastewater on environment: presence of pharmaceuticals, pathogens, and antibiotic-resistance genes. In Current Developments in Biotechnology and Bioengineering (pp. 79-102). Elsevier. **https://doi.org/10.1016/B978-0-12-819722-6.00003-1**

[3] Top S., Akgün M., Kıpçak E., Bilgili M. S. (2020). Treatment of hospital wastewater by supercritical water oxidation process. Water Research 185(15), 116279. **https://doi.org/10.1016/j.watres.2020.116279**

[4] Moyel M. S., Akbar M. M., Hussain N. A. (2023). Evaluation of spatio-temporal changes in water quality in the middle section of the Shatt al-Arab River, Southern Iraq. Journal of Ecological Engineering. 24(4), 297–311 **https://doi.org/10.12911/22998993/161014**

[5] Allafta, H., Opp, C. (2020). Spatio-temporal variability and pollution sources identification of the surface sediments of Shatt Al-Arab River, Southern Iraq. *Sci Rep* 10, 6979. **https://doi.org/10.1038/s41598-020-63893-w**

[6] Al-Miyahi, E. K. A. (2016). The impact of liquid medical pollutants generated from governmental hospitals on aquatic environmental pollution in Basrah City (Unpublished master's thesis). University of Basrah.

[7] Al-Enazi, M. S. (2016). Evaluation of wastewater discharge from Al-Sadr Teaching Hospital and its impact on the Al-Khorah Channel and Shatt Al-Arab

River in Basra City, Iraq. Journal of Environment and Earth Science, 6(12), 55–65.

[8] Al-Khafaji, S. A., Al-Rekabi, W. S., & Abbas, S. A. (2023). Evaluation of the efficiency of the Al-Mauany Hospital sewage treatment plant in Basrah City. IOP Conference Series: Earth and Environmental Science, 1215, 012051.

[9] Alsingery, B. R., Alabbawy, D. A., & Almahmoo, H. K. (2023). Assessment of sanitation system flowing water characteristics in selected hospitals in Basra City, Iraq. IOP Conference Series: Earth and Environmental Science, 1215, 012051.

[10] Al-Sultan, A. A., Kadhem, R. J., & Alabdraba, W. M. Sh. (2017). Evaluation of the quality of disposed wastewater in selected hospitals in Baghdad City. Journal of Environmental Studies, 17, 35–41.

[11] Al-Ajlouni, K., Shakhatreh, S., Al-Ibraheem, N., & Jawarneh, M. (2013). Evaluation of wastewater discharge from hospitals in Amman, Jordan. International Journal of Basic & Applied Sciences, 13(4), 44–52.

[12] Bimeyimana, A., Maniragaba, A., Mupenzi, C., & Bazambanza, A. (2020). Physico-chemical and bacteriological analysis of wastewater from hospital: Case of Centre University Teaching Hospital of Kigali. International Journal of Environmental & Agriculture Research, 6(3), 20–32.

[13] World Health Organization. (2014). Safe management of wastes from health-care activities (2nd ed.). WHO Press.

[14] Verlicchi, P., & Grillini, V. (2017). Hospital wastewater treatments adopted in Asia, Africa, and Australia. In The Handbook of Environmental Chemistry (Vol. 60, pp. 171–188). Springer.

[15] Paucar, N. E., Verlicchi, P., & Zanni, G. (2020). A review on hospital wastewater treatment: Recent achievements and future perspectives. Journal of Environmental Management, 277, 111399.

[16] Farah Mahdi, Ban Abdul Razzaq1, Maytham Sultan (2023). Assessment of Shatt Al-Arab water quality using water quality index and GIS techniques. Iraqi Journal of Science, 2023, Vol. 64, No. 1, pp: 480-491. **https://doi.org/10.24996/ijs.2023.64.1.42**

[17] Yu-Pin Lin, Hone-Jay Chu, Chen-Fa Wu, Tsun-Kuo Chang and Chiu-Yang Chen (2011). Hotspot Analysis of Spatial Environmental Pollutants Using Kernel Density Estimation and Geostatistical Techniques. Int. J. Environ. Res. Public Health 2011, 8, 75-88. **https://doi.org/10.3390/ijerph8010075**

[18] ESRI. (n.d.). Spatial analysis in ArcGIS Pro. ArcGIS Pro Documentation. Retrieved December 1, 2025, from **https://pro.arcgis.com/en/pro-app/latest/help/analysis/introduction/spatial-analysis-in-arcgis-pro.htm**

[19] Al-Asadi, S.A.R. and Alhello, A.A. (2019) 'General assessment of Shatt Al-Arab River, Iraq'. Int. J. Water, Vol. 13, No. 4, pp.360–375.

[20] APHA (2017). Standard Methods for the Examination of Water and Wastewater (23rd ed.). American Public Health Association. **https://www.standardmethods.org**

[21] Metcalf & Eddy (2014). *Wastewater Engineering: Treatment and Resource Recovery* (5th ed.). McGraw-Hill Education.

[22] ESRI (2023). *Buffer Analysis—ArcGIS Pro Documentation*.https://pro.arcgis.com/en/pro-app/latest/tool-reference/analysis/buffer.htm

[23] Ali, S. H., Najemaden, M. A., & Ahmed, R. T. (2018). Using GIS techniques for mapping the pollution of particulate materials in Kirkuk. *Sustainable Resources Management Journal*, 3(2),

58–66. https://doi.org/10.5281/zenodo.1287926

[24] Li, J., & Heap, A. D. (2014). Spatial interpolation methods applied in the environmental sciences: A review. *Environmental Modelling & Software*, 53, 173–189.

[25] ESRI (2023). *Kernel Density—Spatial Analyst Tools*.https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/kernel-density.htm

[26] Silverman, B. W. (1986). *Density Estimation for Statistics and Data Analysis*. Chapman & Hall. https://www.crcpress.com/Density-Estimation-for-Statistics-and-Data-Analysis/Silverman/p/book/9780412246203

[27] World Health Organization. (2006). WHO Guidelines for the Safe Use of Wastewater, Excreta and Greywater (Vol. 2). WHO Press. https://www.who.int/publications/i/item/9241546832

Appendix A

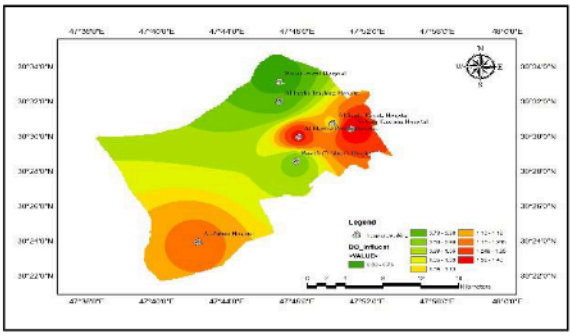

Fig. A.1 spatial interpolation of DO influent

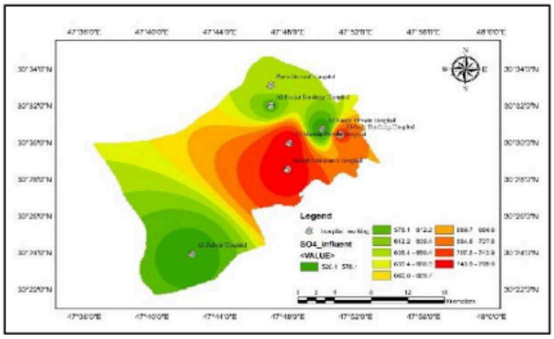

Fig. A.2: spatial interpolation of So4 influent

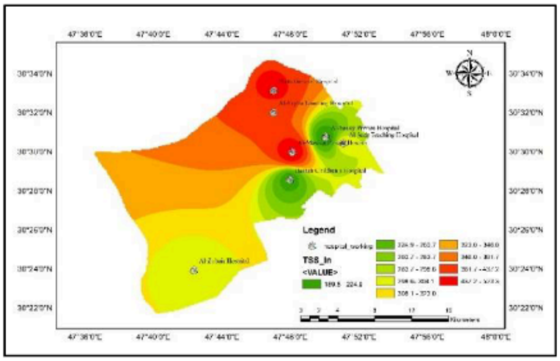

Fig. A.3: spatial interpolation of TSS (mg/l) influent

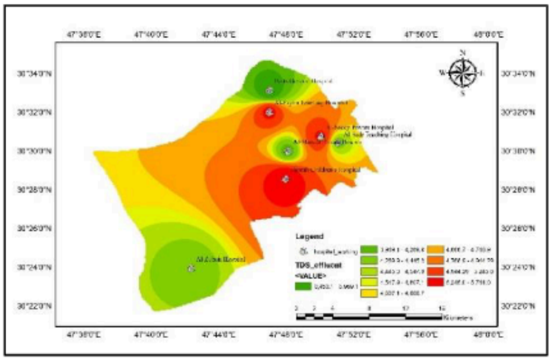

Fig. A.4: Spatial interpolation of TDS influent

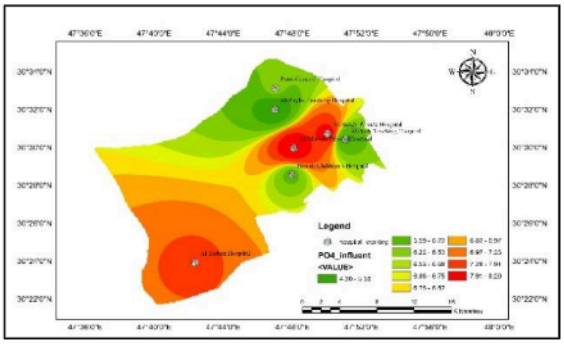

Fig. A.5: spatial interpolation of Po4 influent

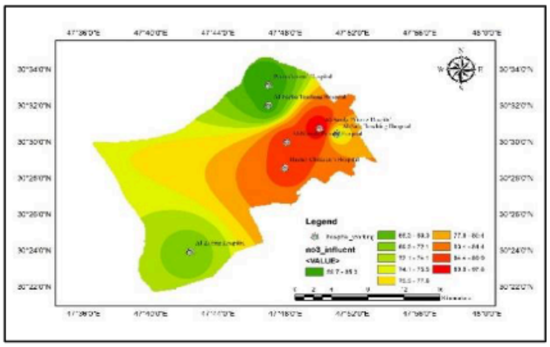

Fig. A.6: spatial interpolation of No3 influent

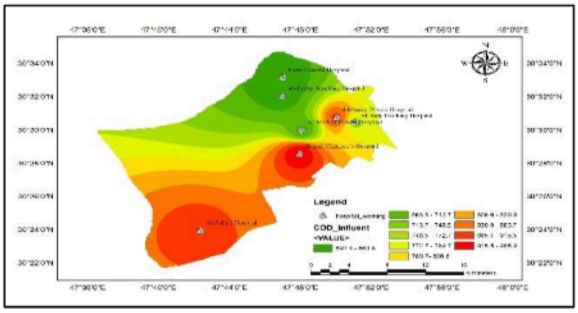

Fig. A.7: spatial interpolation of COD influent

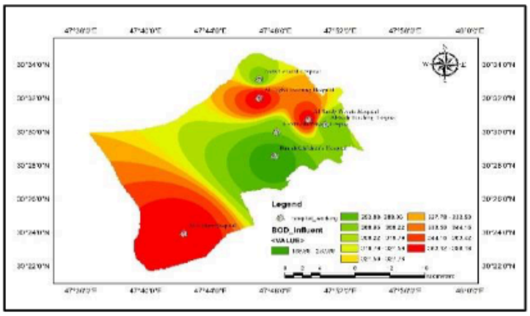

Fig.A.8: spatial interpolation of BOD influent

Appendix B

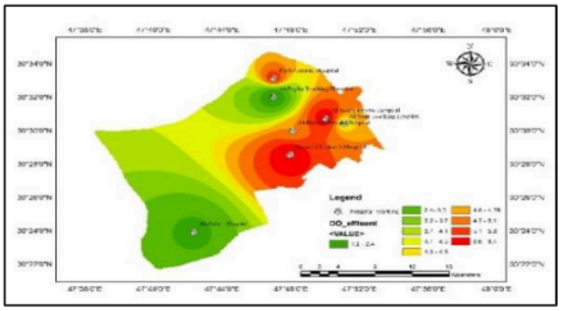

Fig. B.1: Spatial distribution of DO effluent

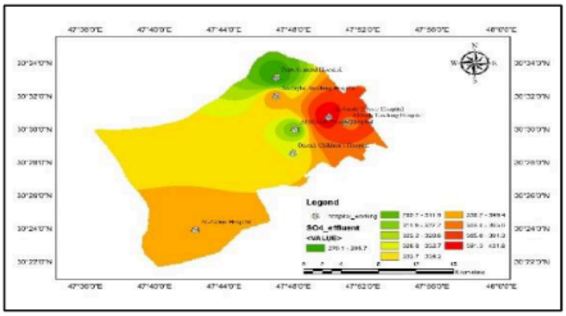

Fig. B.2: spatial distribution of SO4 effluent

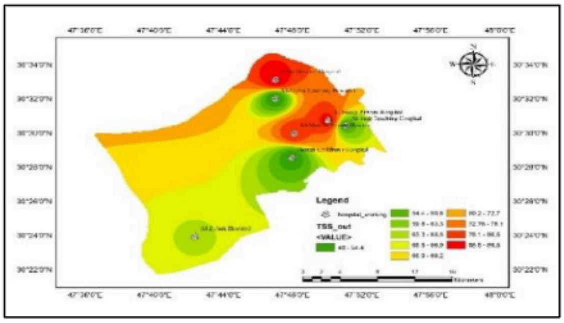

Fig. B.3: Spatial distribution of TSS effluent

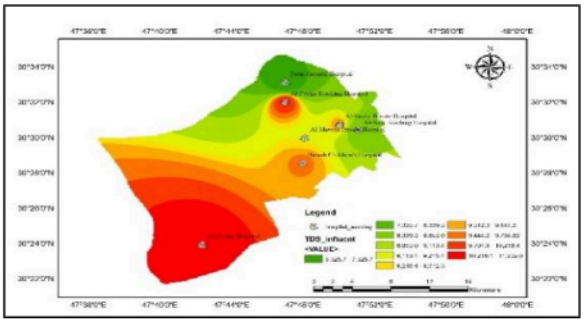

Fig. B.4: Spatial distribution of TDS effluent

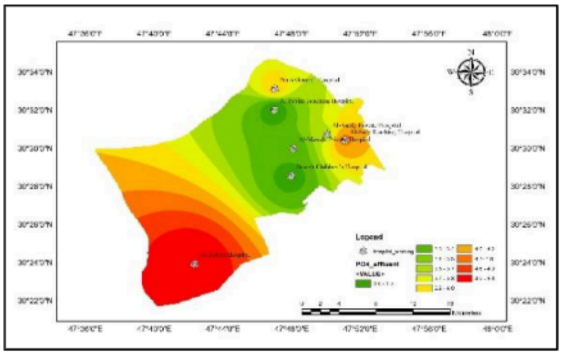

Fig. B.5: Spatial distribution of PO4 effluent

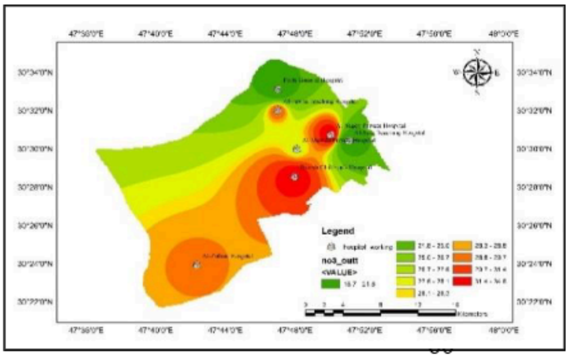

Fig. B.6: Spatial distribution of NO3 effluent

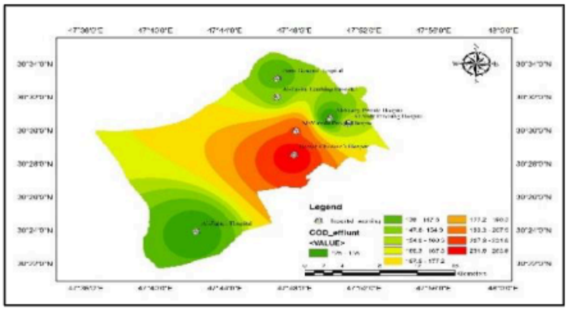

Fig. B.7: Spatial distribution of COD effluent

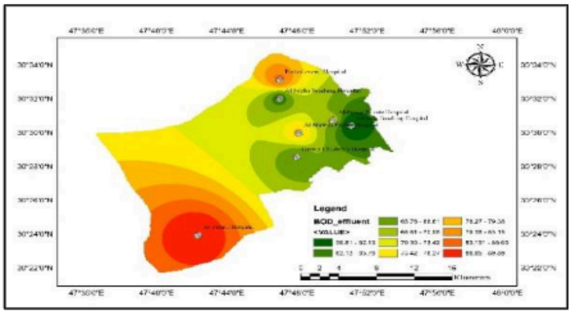

Fig. B.8: Spatial distribution of BOD effluent