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LETTER

Exploring pesticide transport, groundwater, and environmental justice in a changing climate: a community engaged research approach

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Abstract

The pressing issue of pesticide exposure disproportionately affecting marginalized communities underscores the immediate necessity to tackle pesticide drift from nearby agricultural areas, especially aggravated by the impacts of climate change. Effective measures including stricter regulations, enhanced monitoring, alternative agricultural practices, and community engagement are essential to mitigate environmental injustices and safeguard community health. This article delves into the intricate relationship between pesticide transport, groundwater vulnerability, and environmental justice within the context of climate change. Employing a geospatial analytical hierarchy overlay model, we comprehensively assess the impact of pesticide transport on groundwater vulnerability while scrutinizing climate change and associated environmental justice concerns. Groundwater vulnerability across the Kentucky River Basin varies, with 18% classified as very low, 23% as low, 27% as prone, and 20% and 12% as high and very high, respectively, concentrated mainly in the mid-eastern and southern regions due to population density and biodiversity. The research integrates a robust analytical detection technique, with a focus on glyphosate and its metabolites concentrations, to validate and refine spatial models. By engaging with communities, this study enhances understanding of environmental complexities, offering insights for sustainable environmental management.

1. Introduction

Non-point source runoffs such as glyphosate and glufosinate contaminate surface and groundwater used for drinking [1]. Glyphosate and glufosinate are nonselective post-emergence alternatives to traditional organochlorine pesticides due to resistant crop varieties in minimizing crop losses caused by harmful organisms and pests [2–4]. Glyphosate and its metabolite, aminomethylphosphonic acid (AMPA), are frequently detected in surface and ground waters due to widespread use in agriculture, industry, and households, increasing the risk of environmental toxicity [5, 6]. Poiger *et al* [7] detected the presence of glyphosate in the effluent of wastewater treatment plants highlighting glyphosate persistence after remediation and contributions to surface water. Additionally, a significant portion of Kentucky's drinking water is sourced from surface and groundwater supplies, the presence of glyphosate contamination raises notable concerns for effective monitoring tools and protocols [8].

Researchers have developed methods to quantify glyphosate, glufosinate, and AMPA levels in surface and groundwater, addressing the limitations in regulatory benchmarks [9]. Traditional technologies like gas chromatography are used, but recent advancements have combined derivatization techniques with liquid chromatography tandem mass

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spectrometry (LC-MS/MS) [10–12]. The use of LC-MS/MS improves the sensitivity and selectivity of detecting glyphosate, glufosinate, and AMPA in water [13]. A previous study showcased a robust pre-column detection method using LC-MS/MS, achieving quantification limits of 0.12 $\mu g\ l^{-1}$ [9]. This method allows for accurate measurement and monitoring of trace levels of glyphosate, glufosinate, and AMPA, which is critical for assessing the vulnerability of surface and groundwater sources.

Geospatial modeling via Saaty's Analytical Hierarchy Process (AHP) reveals a significant correlation between groundwater vulnerability, climate change-induced pesticide transport, and challenges to marginalized populations' quality of life [14]. Groundwater vulnerability is a pressing concern due to rapid agriculture production, population growth, and climate change's impact on water cycle and runoff from intensified rains [15]. Unpredictable climate change patterns contribute to increased pesticide transportation through runoff and leaching, which disproportionately affects marginalized areas [16]. Due to their closeness to agricultural districts with significant pesticide usage, Black, Indigenous, and People of Color (BIPOC) and economically marginalized populations are frequently the most affected [17]. Rising precipitation and climate-related floods can transport pesticides, potentially contaminating groundwater and increase citizens' concerns of water quality and perpetuating environmental injustice [18].

BIPOC and marginalized communities continue to encounter obstacles stemming from contaminated groundwater, which are exacerbated by the lack of resources and remediation assistance [19]. Addressing these disparities requires readily available data driven models to support the development of comprehensive policies, strengthened environmental regulations, and active community involvement. Community-engaged research is a crucial bridge between technical expertise and community empowerment in addressing environmental justice concerns for equitable outcomes [20].

This study investigates the intricate relationship between pesticide transport, groundwater vulnerability, and environmental justice in the context of climate change. To comprehensively assess the influence of pesticide transport on groundwater vulnerability, this study uses a geospatial analytical hierarchy overlay model. Pesticide transport, climate change, and related environmental justice issues are investigated. Furthermore, the research uses a robust analytical detection technique, specifically focusing on glyphosate and its metabolites concentrations, to validate and refine the developed spatial models. The study intends to enhance our understanding of the environmental complexities involved by contributing valuable insights for sustainable environmental implementation and management.

Table 1. Key demographic, economic, and environmental characteristics of the two counties and their respective watersheds [25].

Parameter	Fayette County, KY	Woodford County, KY
Racial/Ethnic Composition	White (70%), Black or African American (15%), Asian (4%), Hispanic (2.8%)	White (86%), Black or African American (3.9%), Asian (2.7%), Hispanic (4.7%)
Median Household Income	$61 526	$49 000
Characteristics of Sampling Points	High urbanization and mixed forest	High agriculture and mixed forest
Economic Significance	Reserve for distilleries, grist mills, horse farms, and crop irrigation	Agricultural and horse pastures

2. Methodology

2.1. Geospatial analytical hierarchy overlay model: framework and implementation

2.1.1. Case study locations

The Kentucky River Basin, spanning 7000 square miles in northeastern Kentucky, is renowned for its rolling hills, forests, farmlands, and abundant waterways, with the central artery being the Kentucky River, which joins the Ohio River in Carrollton [21]. The basin is crucial for ecosystems, aquatic life, local communities, and the state's economy, providing water for drinking, industrial use, and agriculture [22]. Water samples were collected in two of its watersheds for the monitoring of glyphosate—Cane Run and Royal Spring, and Camden Creek (table 1).

Cane Run and Royal Spring are groundwater networks in Kentucky's Inner Bluegrass Region (figure 1) (Fayette and Scott counties), characterized by agricultural land use, urbanized headwaters, temperate climate, and moderately deep, well-drained soils supported by Middle Ordovician phosphatic limestone [23]. Two of the sampling points, near a printer company (PRINT) and a horse park (KYHP), were in highly dense urban areas whereas the other locations were in high agriculture and mixed forest areas. The Camden Creek watershed in Woodford County, Kentucky (figure 1), is the drainage basin for a significant portion of the C. Oran Little farm, covering 4.2 square miles in total [24].

2.1.2. Watershed vulnerability indexing

The delineation of watershed boundaries was conducted using ArcMap for Windows Software

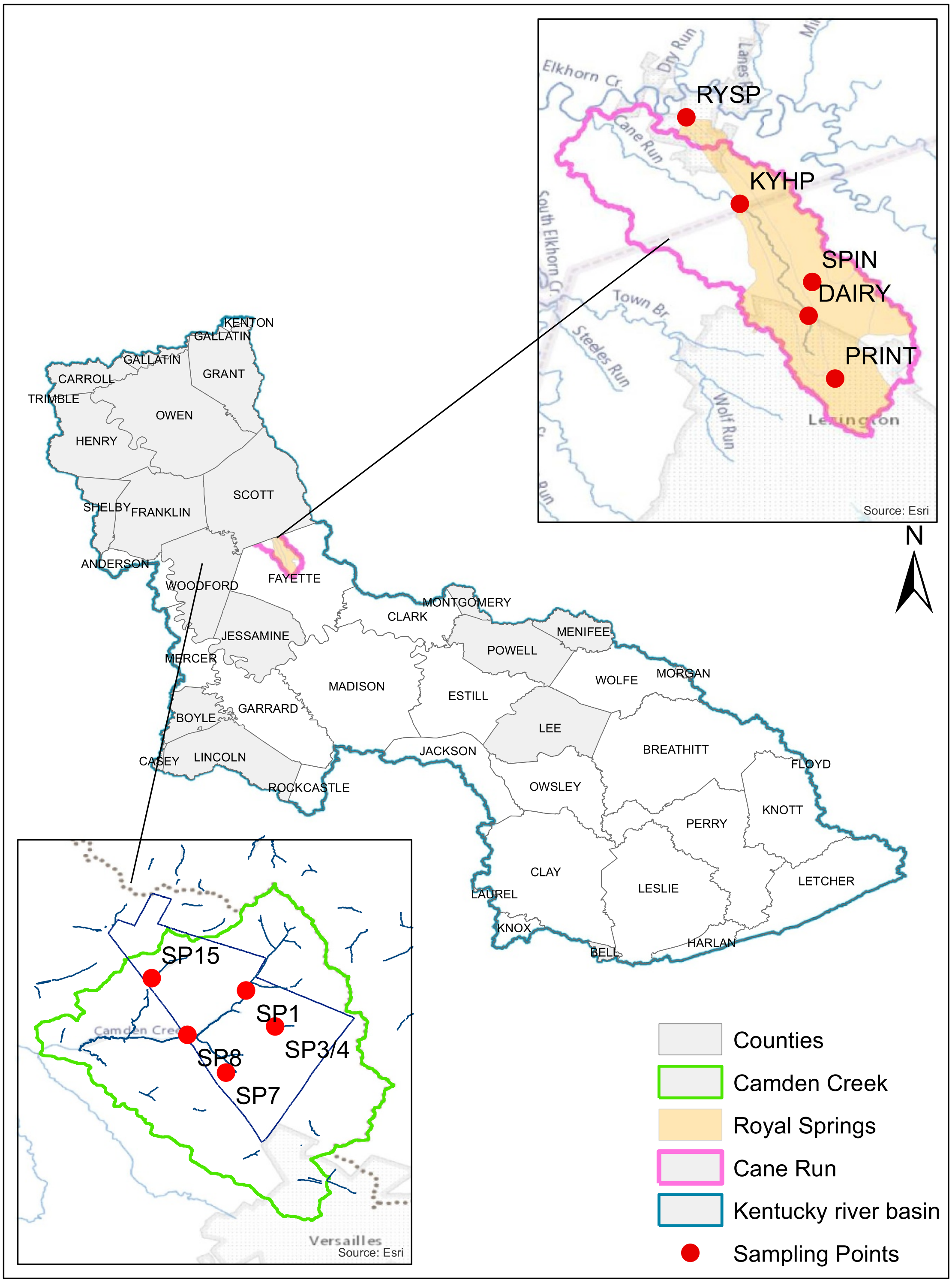

Figure 1. Map of Kentucky River Basin, Camden Creek and cane run and royal spring watersheds.

(Version 10) by the Environmental System Research Institute (Redlands, CA, USA), with data processed through ArcGIS software and transformed into GCS_WGS_1984 coordinates projection for housing federally mapped data perta compatibility.

Seven thematic layers [slope, precipitation, land use/land cover (LULC), population density, infiltration, drainage density, and lineament density] were employed to assess the hydrogeological and anthropogenic influences on glyphosate transport in karst watersheds, ensuring that the shortfalls of existing models were accounted for in the proposed model (table 2) [26]. Relevant data were extracted from remote sensed digital elevation models and historical geological and topographical records, sourced from the Kentucky Geological Survey's KYGeoNet portal, housing federally mapped data pertaining to Kentucky.

Table 2. Regional guide for the selection of thematic layers [26].

Thematic layers	Overlay groundwater vulnerability index assessment tools: Proposed Model	DRASTIC [27]	GOD [28]	SINTACS [29]	EPIK [30]	PI [31]	ISIS [32]	AVI [33]
Slope (degree)	✓	✓		✓				
Lineament Density (m^{-1})	✓	✓	✓	✓	✓		✓	✓
Drainage Density (m^{-1})	✓	✓	✓	✓	✓			
LULC	✓				✓	✓	✓	
Infiltration	✓	✓	✓	✓	✓	✓	✓	✓
Precipitation (mm)	✓	✓		✓				
Population Density (people km^{-2})	✓							✓

Table 3. Rating score of Saaty's analytical hierarchical process (IV = Intermediate values) [34].

Score	1	2	3	4	5	6	7	8	9
Degree of Preference	Equal	IV	Moderate	IV	Strong	IV	Very Strong	IV	Extreme

Table 4. Saaty's analytical hierarchy process pairwise comparison of slope classes.

	Pairwise comparisons										
	Class Number	1	2	3	4	5	6	7	8	9	
Class Number	Class Description (degree)	<0.57	0.58–1.1	1.2–1.8	1.9–2.5	2.6–3.2	3.3–4.2	4.3–5.6	5.7–8.4	8.5–13	Weight
1	<0.57	1.00	0.50	0.33	0.25	0.20	0.17	0.14	0.13	0.11	2%
2	0.58–1.1	2.00	1.00	0.50	0.33	0.25	0.20	0.17	0.14	0.13	3%
3	1.2–1.8	3.00	2.00	1.00	0.50	0.33	0.25	0.20	0.17	0.14	4%
4	1.9–2.5	4.00	3.00	2.00	1.00	0.50	0.33	0.25	0.20	0.17	6%
5	2.6–3.2	5.00	4.00	3.00	2.00	1.00	0.50	0.33	0.25	0.20	8%
6	3.3–4.2	6.00	5.00	4.00	3.00	2.00	1.00	0.50	0.33	0.25	12%
7	4.3–5.6	7.00	6.00	5.00	4.00	3.00	2.00	1.00	0.50	0.33	16%
8	5.7–8.4	2.00	7.00	6.00	5.00	4.00	3.00	2.00	1.00	0.50	21%
9	8.5–13	1.00	8.00	7.00	6.00	5.00	4.00	3.00	2.00	1.00	29%
	CR Value	−0.19									

Classes within each thematic layer were created and scored using the Saaty's scale ranging from 1–9 (table 3) [34]. High Saaty's scores were assigned to higher classes within the thematic layers of slope, lineament, drainage density, infiltration, precipitation, and population density (tables 4 and S1–S5). Table 4 demonstrates the pairwise comparison of the nine different slope classes. The higher classes in each thematic layer exert a greater influence on contamination vulnerability, attributed to the swift movement of pesticides [35]. The LULC classes were developed based on increasing glyphosate usage leading to the transport of pesticides and groundwater contamination (table S6) [26].

The seven thematic layers were grouped into three categories—(1) public health influence (population density), (2) pesticide runoff and groundwater interaction initiators (precipitation, infiltration and LULC) and (3) topographical influences (slope, drainage, and lineament densities). Population density was scored highest in the thematic layer comparison matrix to provide a comprehensive understanding of groundwater vulnerability by capturing the multifaceted interactions between human activities, land use, and potential contamination risks (table S7). Population density is a crucial parameter for local stakeholders and its inclusion considers their concerns and priorities, thereby validating goals and characteristics of the study area [36]. Prioritizing pesticide runoff and groundwater interaction initiators over topographical influences enhanced the assessment's relevance by focusing on direct contamination pathways [37].

Precipitation was then scored higher than infiltration and LULC due to its direct impact on recharge and connection to the hydrological cycle which heavily influences contaminant transport in groundwater connectivity [38]. Infiltration received a higher score than LULC owing to its intermediate role in initiating and transporting pesticides in groundwater vulnerability, particularly within a well-developed karst basin [39]. This prioritization ensures a more precise depiction of the factors driven by runoff that influence groundwater vulnerability. In evaluating topographical influences, the highest score was assigned to drainage density, followed by lineament density, and then slope. Drainage density increases connectivity between groundwater and surface water systems, enhancing the potential for contaminants to reach groundwater through surface runoff [37]. Lineament density influences groundwater flow patterns and contributes to contaminants' movement whereas slope influences runoff speed and surface water interaction [40]. Drainage density, lineament density, and slope are all measurable parameters, enhancing the quantitative aspect of the vulnerability assessment. The groundwater vulnerability index (GVI) was calculated by summing each thematic layer's AHP weight and Saaty's score of each thematic layer weighted values, as illustrated in equation (1). This process facilitated the segmentation of the entire study area into distinct GVI zones.

$$\begin{aligned}&\text{Groundwater Vulnerabiliy Index (GVI)}\\&= S_wS_c + LU_wLU_c + L_wL_c + I_wI_c + D_wD_c\\&\quad + R_wR_c + P_wP_c \qquad (1)\end{aligned}$$

where land slope = S (degrees), land cover/use = LU, lineament (meter^{-1}) = L (meters), infiltration = I, precipitation = R (millimeters), population density = P (people/kilometer^2), and drainage density to groundwater = D (meter^1). AHP weight of each layer = 'w', Saaty's score of individual thematic layer = 'c'

The model validation process utilized map removal sensitivity analysis to assess the vulnerability map's robustness by systematically removing thematic layers and comparing original and modified models to determine each layer's impact on accuracy, identifying crucial maps for precise spatial mapping. JMP statistical software was utilized for spatial variance and robustness evaluations using Dunnett's test, alongside geospatial correlation analysis to understand groundwater vulnerability's interaction with environmental justice, guiding environmental policy decisions. Spatial analysis investigated the overlap between highly vulnerable areas and federally designated opportunity zones [41], enhancing understanding for management decisions. The uncertainty of the GVI was quantified through the calculation of the consistency ratio (CR) of the AHP matrix (equation (2)).

$$CR = (\lambda \max - n) / [(n-1) * \text{RI}] \qquad (2)$$

where λmax = maximum eigenvalue of pairwise comparison matrix, n = number of criteria being compared, and Random Index = RI (pre-determined for 7 thematic layers = 1.3) [28]. If the CR is less than or equal to 0.1, the judgments are considered consistent and reliable.

2.2. Analytical detection techniques for glyphosate and metabolites concentrations

The Environmental Protection Agency (EPA) surface water sampling protocol and section 8 of EPA Method 547 for glyphosate assessment in drinking water were followed in the collection of surface and groundwater grab samples [42, 43]. A YSI multiparameter meter was used to measure temperature, conductivity, dissolved oxygen, salinity, total dissolved solids, chloride, and ammonia levels at each sampling point. The study used a pre-column derivatization protocol developed by Martin *et al* [9]. The sample was transferred into an amber glass bottle, supplemented with 800 μl of isotope internal standard solution. 9-fluorenylmethyloxycarbonyl chloride, ethylenediaminetetraacetic acid and borate solutions were then added. The samples were incubated in a water bath at 40 °C in darkness for 4 h, then phosphoric acid solution was added and stored at 4 °C. The study used an Agilent Series 1290 LC coupled with an Agilent 6470A triple quadrupole mass spectrometer. The drying gas flow rate was set at 5 l min^{-1} at 300 °C, with a nebulizer pressure of 45 psi and a fragmentor voltage of 110 V. Agilent Masshunter Qualitative and Quantitative software was used for processing the chromatographic results. A Phenomenex Gemini NX-C18 column was used, with each injection containing 20 μl matrix/sample and maintaining a column compartment temperature of 30 °C.

2.3. Community-centered approach in research design

Community-engaged research emphasizes collaboration with communities to address social and environmental issues, particularly focusing on marginalized and vulnerable populations [44]. Embracing a community-centered approach in the research design ensured the active engagement and collaboration of various stakeholders to comprehensively address environmental concerns within the community [45]. Whyte, Greenwood, and Lazes [45] outline Participatory Action Research as a methodology that combines practice with scientific research. It involves community members as co-researchers, ensuring that research questions, methods, and outcomes are relevant and beneficial to the community. By leveraging partnerships with key entities such as the Georgetown water treatment plant (RYSP), University of Kentucky research farms (DAIRY and SPIN), and the Cooperative Extension Service Program (all sites in Camden creek), a holistic understanding of the local landscape, including areas of need, contaminants of concern, and prevalent societal practices, was achieved. This collaborative endeavor not only facilitated the identification of pressing environmental issues but also allowed for the exploration of underlying socio-economic factors that influence environmental health. Through ongoing dialogue and consultation with community leaders and stakeholders, shared understanding of priorities emerged, guiding the direction of the research process.

Informed by insights gleaned from community engagement initiatives, sampling efforts were strategically directed towards sites of interests formed by community leaders. This targeted approach ensured that research activities were not only scientifically rigorous but also directly relevant to the lived experiences and concerns of residents. By centering the research design around community needs and perspectives, the study sought to foster a sense of ownership and empowerment among community members, positioning them as active participants in the research process rather than passive subjects.

Furthermore, the collaborative nature of the research endeavor facilitated knowledge exchange and capacity-building initiatives within the community. A partnership with a local high school, STEAM Academy in Lexington, KY, not only facilitated data collection but also ensured effective dissemination of knowledge within the community. By engaging with vulnerable communities and building local capacity, the research fostered collaborative relationships and aimed to lay the foundation for sustainable, community-driven solutions to environmental challenges.

3. Results and findings

3.1. Spatial mapping of pesticide transport and groundwater vulnerability

A significant portion of the Kentucky River Basin lies within the $<1.8°$ slope category, predominantly in the northern regions, where the slope is gentlest, and the topographic elevation is lowest. Higher slope classes are primarily found in the southeastern areas of the basin (figure 2(a)). Effective pesticide application promotes agricultural productivity; however, steep slopes can alter subsurface water movement, preventing intended use on application site. This, in turn, jeopardizes food production and security [46]. The lineament densities across the basin range from 0.1 to 19 m^{-1} (figure 2(b)). The study reveals a decrease in lineament density towards the southwest, while higher density is observed in the northeastern regions, forming an elongated shape. Particularly in regions with a high density of lineaments, lineament density increases the connectedness of subsurface flow routes, enabling pesticides to reach groundwater more quickly and possibly increasing contamination risk [47].

Most of the study area exhibits low to moderate drainage densities (figure 2(c)). Drainage densities <2.4 m^{-1} encompass 66% of the basin area, while densities ranging from 2.5 to 7.1 m^{-1} cover 9%. Additionally, densities between 7.2 and 11 m^{-1} occupy 11% of the area, densities of 12–16 m^{-1} cover 8%, and densities exceeding 17 m^{-1} account for 6% of the basin. The geological and climatic conditions in the watersheds play a significant role in determining channel length which influences drainage density. This is primarily due to the presence of low relief vegetation cover and permeable karst subsurface materials [48]. Urban areas, mixed forests, and agricultural are the main LULC types in the Kentucky basin (figure 2(d)). In contrast, water bodies and wetlands constitute a minor proportion of the overall LULC type. Factors like fertilizer use, forest dynamics, urbanization, and water bodies and wetlands can affect groundwater recharge and ecological balance [1]. Monitoring and managing these areas are crucial for sustainable water resources.

Most of the northern and central sections of the basin are characterized by slow infiltration (Group C, C/D and D) (figure 2(e)). These topographies have poor water-absorbing capacities and restricted drainage, which leads to increased runoff (table S8). The presence of karst plains impacts pesticide drift and groundwater contamination. High infiltration levels in watersheds suggest potential for leaching and runoff, as water and pesticides easily move through soil and aquifer connections [35, 47]. The average annual rainfall observed within the basin showed highest levels in the southern part whilst the northern section experienced the lowest amount of precipitation (figure 2(f)). Groundwater sources are particularly vulnerable to glyphosate contamination due to precipitation-induced runoff, erosion, and leaching [48].

Figure 2(g) highlights the low population densities of 90% of the total Kentucky River Basin area. Fayette county has the highest population density, influenced by historical settlement patterns, economic opportunities, and geographic features [49]. This leads to increased pesticide use, potential exposure, and glyphosate in groundwater due to urban and agricultural activities and raises concerns about water safety and sustainable management, emphasizing the importance of clean water access for human wellbeing [14].

The GVI classification (figure 3) reveals varying risk levels across the study area. The outcomes of the groundwater vulnerability assessment reveal that 18% of the area falls under the very low-risk classification, 23% as low-risk, 27% as prone to risk, and 20% and 12% as high-risk and very high-risk areas, respectively. The CR value for all pairwise matrices were <0.1 showing that the judgments are highly acceptable [50]. The hotspots of risk are predominantly concentrated in the mid-eastern and southeastern portions of the watershed. Fayette county, being the largest in the county population density and rich in biodiversity, was identified as highly susceptible to pesticide exposure [21, 22, 51]. The overlap of biodiversity hotspots, availability of water storage resources, and areas of high-risk pesticide further highlights the urgency of addressing pesticide

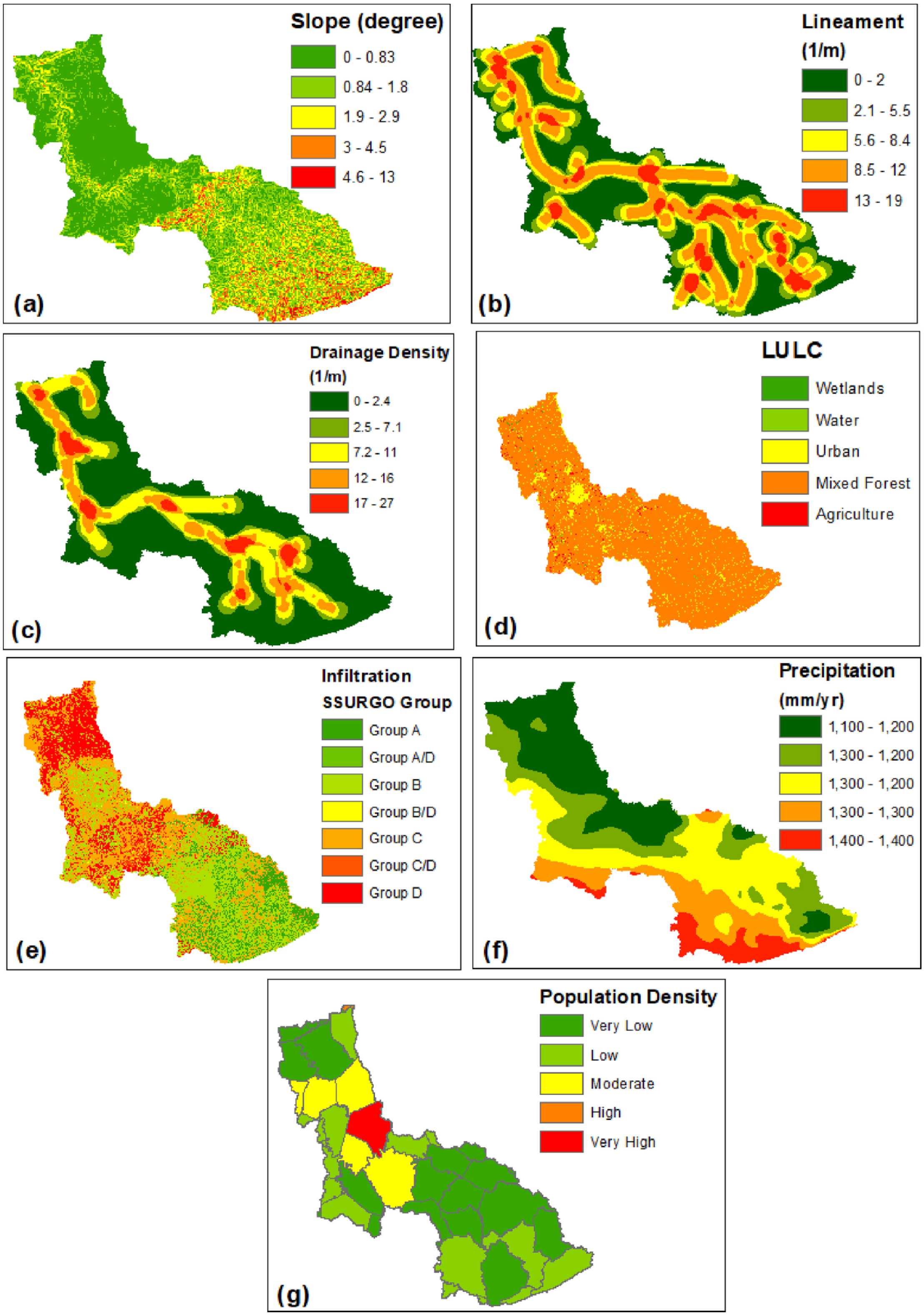

Figure 2. Map of thematic layers including (a) slope, (b) lineament, (c) drainage density, (d) LULC, (e) infiltration, (f) precipitation and (g) population density.

transport. Implementation of precision agriculture techniques and buffer zones around sensitive areas are crucial steps to mitigate glyphosate drift and protect the region's ecological and social sustainability [52]. Areas with karst topography exhibited the highest vulnerability due to the high infiltration and direct contact with routes for the runoff in surface water interaction with groundwater [53–55].

Significant changes in classification of risk areas were seen when any of the thematic layers were removed individually ($p < 0.05$). The results show that these thematic layers affect the movement of

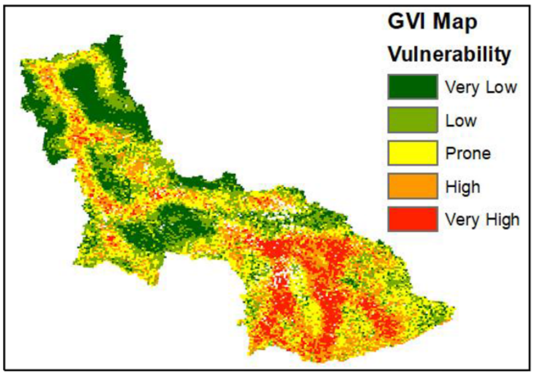

Figure 3. GVI map for Kentucky River Basin.

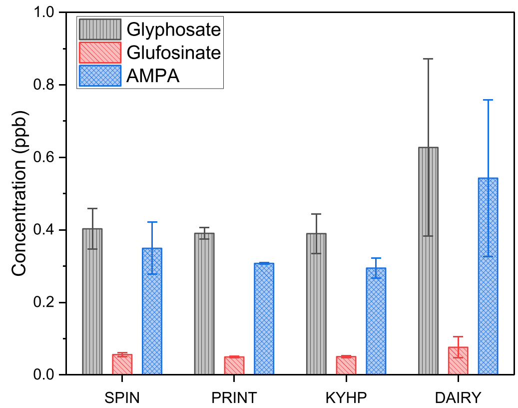

Figure 4. Averaged detected concentration of glyphosate, glufosinate and AMPA from January 2022 to June 2022 in the Cane Run and Royal Spring watershed. (large standard deviation in AMPA and glyphosate concentrations for DAIRY due to significant detection variations).

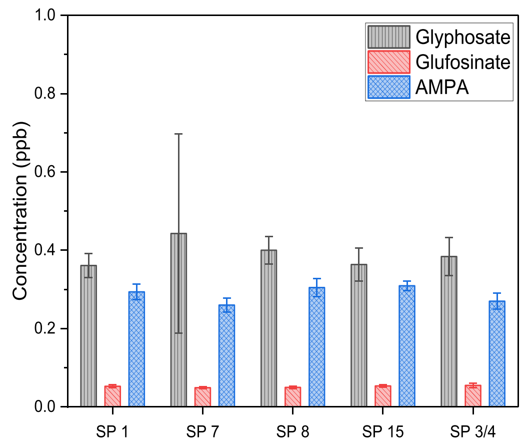

Figure 5. Averaged detected concentration of glyphosate, glufosinate and AMPA from January 2022 to June 2022 in the Camden creek watershed. (large standard deviation in glyphosate concentration for SP 7 due to significant detection variations).

glyphosate within the watershed and have significant influence on the vulnerability of groundwater sources. Glyphosate groundwater contamination posed the biggest threat to individuals in the high populated regions of the watershed, indicating the importance of high scoring and weights associated with the influence of population density. Glyphosate's environmental and health risks are linked to the interdependence of natural and human factors, highlighting the need for optimal management practices to achieve sustainable usage strategies [14]. Public awareness and education about glyphosate hazards and proper handling and disposal methods are also crucial. Implementing climate-resilient practices and sustainable urban design can reduce pesticide usage in agriculture and urban areas during vulnerable times of heavy precipitation [56, 57].

Although high glyphosate usage is usually attributed to high agricultural areas with large-scale intensive farming, high-vulnerability zones were observed in economically non-developed areas with little or no agriculture. Underscoring the occurrence and influence pesticide transport from application regions. Sustainable agriculture, forestry, and water resource management are crucial for biodiversity, climate change, and water protection. Prioritizing responsible consumption, improving laws, and developing collaborations are essential [58]. Continuous monitoring, research, and cooperation are needed for informed decisions, policies, and long-term practices [5, 9].

3.2. Validation of models through glyphosate concentration analysis

The water quality analysis (table S9) revealed that dissolved oxygen levels across all samples exceeded the EPA's minimum requirement for warm water aquatic life (>5 mg l^{-1}) [59], likely influenced by microbial interactions leading to increased glyphosate photodegradation [60]. While most sites met EPA freshwater salinity guidelines, DAIRY and KYHP exhibited elevated salinity, indicating high water hardness and the presence of various metal cations [61, 62]. High water pH inhibited glyphosate uptake, with pH levels within the 6–9 range [63]. Nitrate and ammonia levels generally complied with EPA standards, except for SP7 in the Camden Creek watershed, where ammonia exceeded EPA limits [49]. However, total nitrogen at SP7 remained within WHO guidelines for drinking water [63]. Elevated nitrate-nitrogen concentrations increase the likelihood of detecting mobile pesticides [64], but glufosinate concentrations in sampled watersheds remained below WHO's maximum residue limit [5], suggesting safe exposure levels. There was no discernible pattern of glufosinate concentration fluctuations correlated with rain events, indicating minimal transport from fields to surface water (figures S1 and S2).

Glyphosate was detected in both Camden Creek and Cane Run and Royal Spring watersheds with average concentration of 0.40 ± 0.023 $\mu g\ l^{-1}$ and 0.55 ± 0.11 $\mu g\ l^{-1}$ respectively (figures 4 and 5).

The highest concentrations were found in the highly intensive agriculture sampled sites (DAIRY and SPIN) for the Cane Run and Royal Spring watershed. The average glyphosate concentration detected was higher than the concentration of AMPA found. The relatively high concentrations of glyphosate and AMPA in the downstream sampled outlet sites (PRINT and SP 8) does indicate a potential transfer of these pesticides along the watershed. The inverse proportional trend in glyphosate and AMPA concentrations validates glyphosate as the primary source of AMPA (figures S1 and S2) [5, 9]. The ubiquitous levels of glyphosate and AMPA found in urban sampling locations (PRINT and KYHP) indicate that glyphosate applications used for non-agriculture purposes may have a significant role in the overall pollution of surface waters. This non-point glyphosate contamination sources includes weed control along highways, railways, residential areas, parks, and golf courses [1]. Empirical data from several researchers supports this significant contribution of urban activities [1, 6]. Although the detected levels of glyphosate adhere to the EPA's environmental quality standards, the extensive use of glyphosate in urban settings may pose significant public health risks [60]. This leads to elevated concentrations in surface water, underscoring the necessity for ongoing monitoring and the establishment of sustainable usage practices. Such initiatives are vital for mitigating glyphosate concentrations in areas at heightened risk [5, 15, 19, 52]

3.3. Identification hotspots

A significant section of either prone, high, or very high groundwater vulnerability mapping were found in low population density areas, south of the study area ($p < 0.05$) (figure 6(a)). However, 70% of the most populated county in the basin, Fayette County, was observed to be in the prone, high, or very high GVI classification. This indicates a substantial amount of the population in the basin are potentially exposed to glyphosate contamination given that the Bluegrass area relies on aquifer reserves for public drinking water [51]. Surface water entering the groundwater reserves and aquifers via the predominant karst systems characterizing the basin is most likely the source of the pesticides affecting the human health, environmental quality and socioeconomic development of the area [15].

Despite the usage of glyphosate in the northern section of the watershed, only 22% of the area fall in either prone, high, or very high groundwater vulnerability compared to the 86% of the southern sector which accounts for 21% of the total glyphosate usage (figure 6(b)). The behavior of pesticides in urban catchments is poorly known and documented [65], however the low GVI in application and high usage sites indicate the transport of glyphosate to unintended locations. The transport of glyphosate evidenced by the spatial discrepancy raises concerns about the potential environmental impact of this pesticide movement to the ecological and water quality implications of the watershed [6].

3.4. Identification of environmental justice hotspots

The relationship between pesticide exposure and marginalized communities is intricate. The glyphosate contamination of groundwater sources in the basin disproportionately impacted low-income communities (figures 6(c) and (d)). All federally designated opportunity zones ('economic development tool that allows people to invest in distressed areas in the United States' [66]) fell in either prone, high, or very high groundwater vulnerability (figure 6(c)). This intersection underscores the need for careful planning, community engagement, and sustainable development practices to avoid exacerbating environmental disparities and ensure that economic opportunities are distributed equitably across all communities [18].

Figure 6(e) highlights the relationship between the distribution of BIPOC communities and GVI mapping. A comparison with figures 6(c) and (d) brings forth the intersectionality of the low income and BIPOC areas. Across the Kentucky River Basin, BIPOC communities are dispersed, with notable clusters in the densely populated northwest region. Notably, in the southern part, a cluster of BIPOC communities are found in areas with high populations with low-income status. These regions coincide with hotspots of vulnerability to groundwater contamination. The southern border of the Bluegrass area exhibits high GVI classification, aligning with the predominant residence of BIPOC communities in that area.

The observed correlations between the GVI mapping and environmental justice indicators are the result of historical injustices and contemporary regulatory practices that perpetuate disparities in pesticide exposure and harm [14]. This is critical for comprehending how a variety of factors, including proximity to agricultural activities, occupational pesticide contact, and pollution concentration in marginalized areas, influence these disparities in addition to race and income. This link between BIPOC, low-income communities, and high GVI underscores the persistent environmental injustices these groups endure. This reinforces the urgency for comprehensive solutions addressing both the immediate and enduring effects of pesticide pollution on these communities [14, 15].

In our research, we made it a priority to ensure that the communities we engaged with were informed of the results. After completing the data analysis, we communicated key findings to community stakeholders and intend to make knowledge accessible

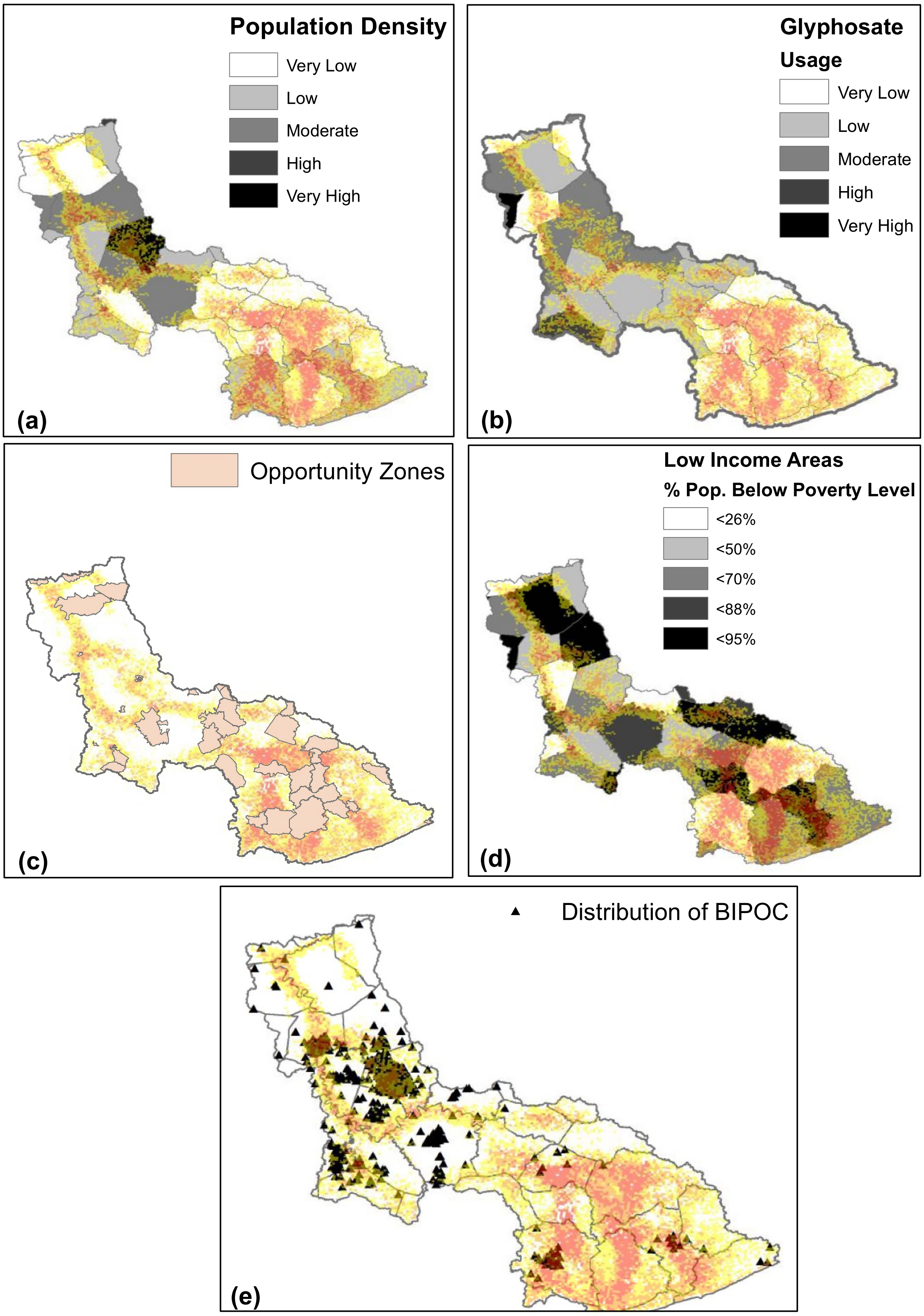

Figure 6. Overlay map of GVI high vulnerability zones on (a) population density, (b) glyphosate usage map, (c) federal opportunity zones, (d) low-income areas map and (e) the distribution of BIPOC communities (GVI map: yellow = prone, orange = high, and red = very high).

manner via social media. As experts on this analysis, we recognize the importance of addressing both historical and present injustices. Based on our findings, we recommend several actionable steps: 1. Policy Advocacy: Advocate for stricter environmental regulations and policies that prioritize the needs of BIPOC communities in the Kentucky River Basin; 2. Community Empowerment: Establish community advisory boards to ensure ongoing engagement and input from residents in decision-making processes; 3. Resource Allocation: Allocate resources for environmental remediation projects in affected areas, ensuring that funding is directed to the most impacted communities; 4. Education and Training: Develop educational programs to raise awareness about environmental justice issues and empower community members with the knowledge and skills to advocate for their rights; 5. Partnerships: Foster partnerships between local government, non-profits, and community groups to create a coordinated response to environmental challenges. By taking these steps, we aim to correct historical wrongs and support sustainable, community-driven solutions to environmental challenges.

4. Conclusion

Future community-engaged environmental engineering projects should prioritize monitoring vulnerable areas for glyphosate contamination, employing geospatial technologies and detection techniques, while involving local communities and stakeholders in decision-making to ensure environmental justice. Advocating for policy reforms and considering climate change's impact on pesticide transport pathways are crucial steps for equitable and sustainable solutions. The research utilizes a multi-disciplinary approach, including geospatial analytical hierarchy overlay models and robust detection techniques, revealing that 59% of the Kentucky basin is moderately or highly vulnerable to groundwater contamination by glyphosate runoff, with most vulnerable areas in the central and southeastern sections. Detected glyphosate and AMPA concentrations were elevated in areas with intensive agriculture, particularly within the Camden Creek, Cane Run, and Royal Spring watersheds, suggesting potential pesticide transfer downstream. Urban areas also exhibited significant glyphosate and AMPA presence, likely from non-agricultural uses. Additionally, the study underscored the unequal distribution of environmental impacts on public health and environmental risks of pesticides, ealsowishtoacknowledgetheparticularly in areas like the Kentucky River Basin, highlighting disparities associated with population density, BIPOC communities, and low-income areas. These findings emphasize the importance of addressing environmental justice issues and ensuring marginalized communities have equitable access to a clean and safe environment, informing more inclusive environmental policies and practices that consider the impact of climate change on pesticide transport.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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