Title: Spatial Analysis of Oil and Gas Production Impact on Surrounding Environment in Texas

INTRODUCTION

Oil and gas production has been a key factor in powering modern society. It provides energy for transportation, heating, electricity, and countless industries. However, while the oil and gas industry bring significant economic benefits, it also has environmental and social consequences. These impacts include pollution of water bodies, disruption of ecosystems, deforestation, and risks to human health, especially in areas close to production sites. Managing these impacts has become an essential task to ensure that oil and gas production is sustainable and minimizes harm to the environment and nearby communities.

Texas, one of the largest oil and gas-producing states in the United States, plays a critical role in meeting global energy needs. The state's rich oil and gas reserves are distributed across vast areas, including rural, agricultural, and urban landscapes. This creates challenges for environmental protection and land-use planning. For instance, oil and gas activities often overlap with ecologically sensitive areas such as wetlands, rivers, and forests. These areas provide essential ecosystem services like water filtration, carbon storage, and biodiversity conservation. Damage to these natural features can have long-term consequences for both local communities and the broader environment.

Moreover, the human dimension of oil and gas production is crucial. Many production sites are located near densely populated areas, where residents may be exposed to risks such as air and water pollution, noise, and industrial accidents. For example, studies have shown that people living near oil and gas production sites are at a higher risk of respiratory illnesses due to exposure to harmful emissions such as methane and volatile organic compounds (VOC) (Blundell et al., 2022). These challenges underline the need for spatial analyses that can identify high-impact zones where environmental and human health risks are greatest.

Geospatial technologies, such as Geographic Information Systems (GIS), provide powerful tools to address these challenges. GIS allows researchers and policymakers to integrate diverse datasets—such as land cover, hydrography, and population density—into a unified framework for analysis. Through spatial modeling, we can identify areas where oil and gas activities have the most significant impact and prioritize them for conservation or mitigation measures.

This study aims to use GIS to analyze the impact of oil and gas production on the surrounding environment in Texas. The project integrates datasets on hydrographic features, land cover types, and population density to identify areas of high sensitivity. By applying a weighted overlay analysis, this research highlights zones where the cumulative impact of oil and gas activities is most significant. The findings aim to guide decision-makers in implementing strategies that balance energy production with environmental protection and public health.

Several previous studies have highlighted the importance of spatial analyses in understanding the environmental impacts of oil and gas production. For instance, a study by Lusweti et al. (2021) used spatial models to assess the impact of oil and gas activities on water quality in shale regions. Similarly, Cheng et al. (2014) reviewed public health risks associated with oil and gas development

and emphasized the need for site-specific risk assessments. This research builds on these efforts by focusing on Texas, a state with unique environmental and demographic characteristics.

In summary, this project addresses three key questions:

1. Which environmental features are most affected by oil and gas activities in Texas?
2. How do hydrographic features, land cover, and population density influence the sensitivity of areas near oil and gas production sites?
3. What strategies can be developed to mitigate the identified impacts while supporting sustainable energy production?

By answering these questions, this study aims to provide actionable insights for policymakers, environmental managers, and energy companies working to balance environmental protection with economic development.

DATA AND METHODS

This section describes the data used and the methods applied to assess the impact of oil and gas production on the surrounding environment in Texas. The analysis integrated hydrographic, land cover, and population datasets with oil and gas well locations to identify high-sensitivity areas. Each dataset underwent pre-processing and spatial analysis using Geographic Information Systems (GIS) tools.

Data Used

i) National Hydrography Dataset (NHD)

- **Description**: The NHD provides hydrographic features such as streams, rivers, and wetlands.
- **Source**: https://prd-tnm.s3.amazonaws.com/index.html?prefix=StagedProducts/Hydrography/NHD/State/Shape/
- **Purpose**: To identify water features that may be sensitive to oil and gas production activities.

ii) National Land Cover Dataset (NLCD)

- **Description**: The NLCD classifies land cover types, such as forests, wetlands, urban areas, and agricultural lands.
- **Source**: Multi-Resolution Land Characteristics Consortium (MRLC), NLCD 2019 Land Cover. Available at: https://www.mrlc.gov/.
- **Purpose**: To assess land-use sensitivity and evaluate how oil and gas production intersects with ecologically significant land cover types.

iii) Population Dataset

- **Description**: Raster data representing population density across Texas.
- **Source**: U.S. Census Bureau.
- **Purpose**: To determine the impact of oil and gas production on human populations, emphasizing areas with high population density.

iv) Oil and Gas Well Locations

- **Description**: Spatial data of oil and gas wells, including their geographic coordinates and attributes.
- **Source**: Texas Oil and Gas Viewer, Texas Railroad Commission. Available at: https://www.arcgis.com/home/item.html?id=6304a76feaa24d98b8eaecdcc0f9e4bc.
- **Purpose**: To serve as the focal points for analyzing spatial relationships with environmental and human features.

Methods

Methods

Step 1: Buffer Creation

- **Process**: A **1/2-mile buffer** was created around each oil and gas well location. (McKenzie et al., 2012).
- **Tool Used**: **Buffer Tool** in ArcGIS Pro.
- **Purpose**: To define areas of influence around each well and identify overlapping environmental features.

Step 2: Intersecting Data with Buffers

- **Process**:
    1. **NLCD Land Cover**:
        - The NLCD raster was clipped to the buffer using the **Extract by Mask** tool.
        - Reclassification was performed to assign sensitivity ranks to land cover types (e.g., forests ranked higher than urban areas).
    2. **NHD Hydrography**:
        - NHD features were clipped to the buffer zone using the **Clip** tool.
        - Sensitivity ranks were assigned based on the type of water feature (e.g., wetlands ranked higher than artificial paths).
    3. **Population Raster**:
        - Population density within the buffer was extracted and reclassified into sensitivity categories (e.g., higher densities received higher ranks).
- **Purpose**: To evaluate how oil and gas activities overlap with sensitive environmental and human features.

Step 3: Weighted Overlay Analysis

- **Process**:
  - The reclassified datasets (land cover, hydrography, and population) were combined using the **Weighted Overlay Tool**.
  - **Weights**:
    - NHD Hydrography: **40%**
    - NLCD Land Cover: **30%**
    - Population Density: **30%**
  - Expression in Raster Calculator:

    Weighted_Overlay = (0.4 * Reclass_NHD) + (0.3 * Reclass_LAND_COVER) + (0.3 * Reclass_Population)

- **Purpose**: To create a single raster layer representing cumulative environmental sensitivity.

Step 4: Zonal Statistics by Census Block

- **Process**:
  - The **Zonal Statistics Tool** was used to compute the **mean ranking** of the weighted overlay raster for each census block.
  - Input:
    - **Feature Zone Layer**: Census block polygons.
    - **Value Raster**: Weighted overlay raster.
  - Output: Each census block was assigned a mean sensitivity value based on the raster values within its boundaries.
- **Purpose**: To aggregate sensitivity rankings to a manageable spatial unit (census blocks).

Step 5: Classification of Risk Zones

- **Process**:
  - Census blocks were classified into **low-risk**, **medium-risk**, and **high-risk zones** based on the mean sensitivity values from Zonal Statistics.
  - Thresholds:
    - **Low Risk**: Mean rank ≤ 3.
    - **Medium Risk**: Mean rank between 4 and 7.
    - **High Risk**: Mean rank ≥ 8.
- **Purpose**: To simplify results for visualization and decision-making.

Step 6: Raster to Polygon Conversion

- **Process**:
  - The weighted overlay raster was converted into polygons using the **Raster to Polygon Tool**.
  - Each polygon was assigned a sensitivity value from the raster, enabling further spatial analysis.

- **Purpose**: To enable vector-based analysis for hotspot detection.

Step 7: Optimized Hotspot Analysis

- **Process**:
  - The **Optimized Hot Spot Analysis Tool** was used to identify statistically significant clusters of high-impact zones from the polygon layer.
  - Input:
    - **Feature Class**: Polygons converted from the weighted overlay raster.
    - **Field**: Sensitivity values from the raster.
  - Output: A map showing optimized hotspot zones, highlighting areas of concentrated environmental sensitivity.
- **Purpose**: To reveal clusters of high-risk zones for better visualization and decision-making.

Step 8: Getis-Ord Gi Hotspot Analysis*

- **Process**:
  - The *Getis-Ord Gi Tool** was applied to the point features generated from the weighted overlay raster to identify spatial clusters of high and low values.
  - Input:
    - **Input Feature Class**: Points converted from the weighted overlay raster.
    - **Field**: Sensitivity values from the raster.
  - Parameters:
    - **Conceptualization of Spatial Relationships**: Fixed Distance Band.
    - **Distance Method**: Euclidean.
    - **Distance Band**: 1/2-mile radius.
  - Output: A hotspot map displaying statistically significant clusters of high (hotspots) and low (coldspots) sensitivity values.
- **Purpose**: To add a statistically robust analysis of high-impact areas.

RESULTS

The analysis produced two maps highlighting the environmental impact of oil and gas production in Texas. These maps—one based on **Optimized Hotspot Analysis** and the other on *Getis-Ord Gi Hotspot Analysis**—show zones classified as **high-impact**, **low-impact**, or **not significant** based on cumulative sensitivity scores derived from hydrographic, land cover, and population datasets. Below is an explanation of the findings from these analyses.

1. **Optimized Hotspot Analysis**

The optimized hotspot analysis identifies clusters of environmental sensitivity and highlights areas where the cumulative impact of oil and gas production is statistically significant.

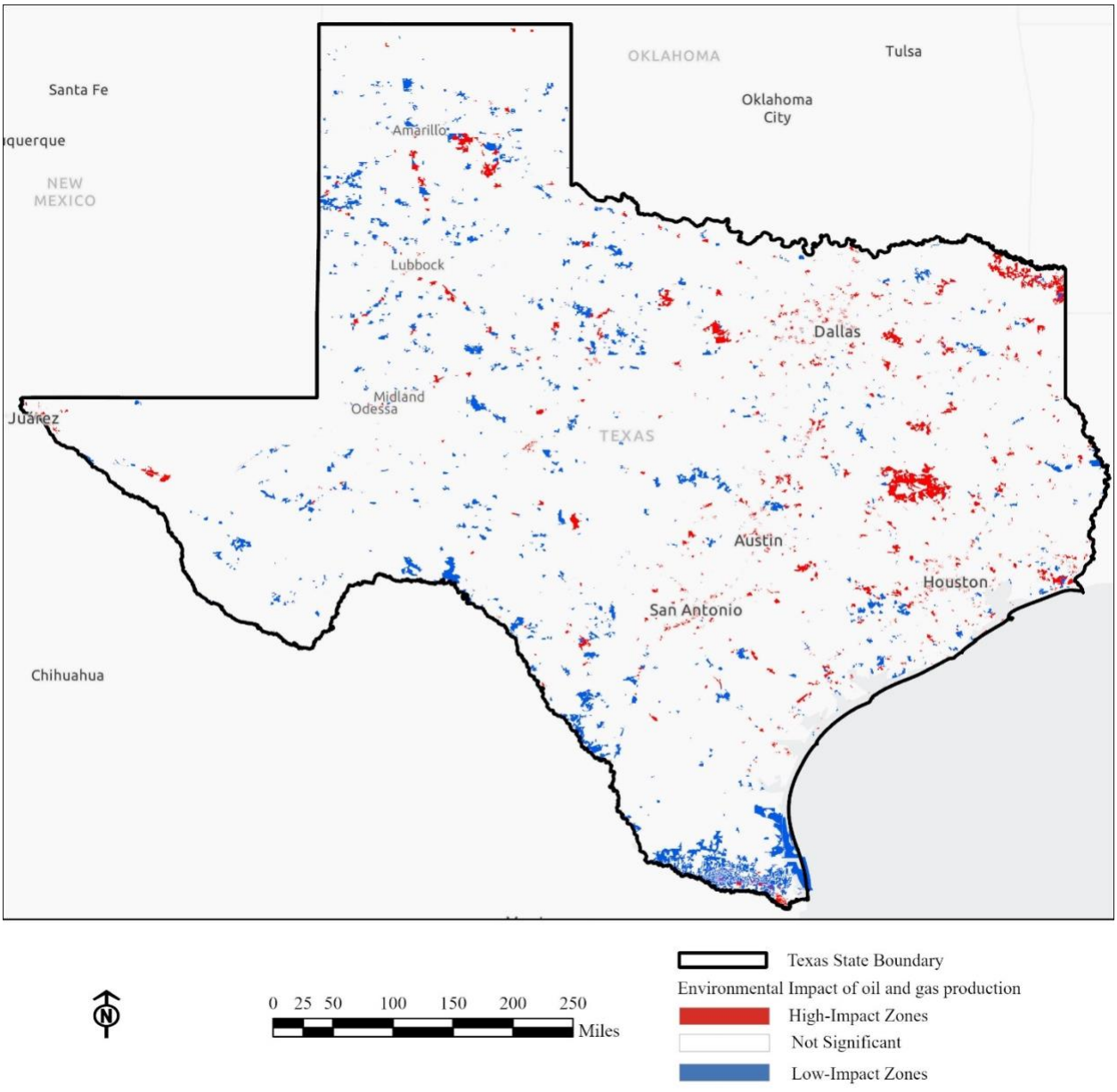


Figure 1: Optimized Hotspot Analysis Map Showing High-Impact, Low-Impact, and Not Significant Zones for Oil and Gas Production in Texas

Findings:

- **High-Impact Zones (Red)**:
  - These zones are clustered in urban areas, especially near **Houston**, **Dallas**, **Austin**, and **San Antonio**. The proximity of these areas to sensitive hydrographic features, such as wetlands and streams, combined with high population density, makes them critical zones for environmental protection.
  - High-impact clusters are also evident in South Texas along the Gulf Coast, where wetlands are prominent and oil and gas activities are extensive.
- **Low-Impact Zones (Blue)**:
  - Found primarily in rural regions, especially in **West Texas**, where oil and gas wells are located in barren lands or sparsely populated areas.
  - These zones represent areas with minimal environmental sensitivity and lower ecological or human impact.
- **Not Significant Zones (White)**:
  - Areas without notable clustering of sensitive environmental features or oil and gas wells. These are spread across the state.

Interpretation:

The optimized hotspot map provides a general overview of areas requiring further attention or policy intervention. Urban centers and regions with overlapping sensitive features are highlighted as high-priority zones for environmental management.

*2. **Getis-Ord Gi Hotspot Analysis****

The Getis-Ord Gi* analysis complements the optimized hotspot map by providing statistically robust clusters of environmental sensitivity. It evaluates spatial relationships between points and identifies zones of high and low impact with greater precision.

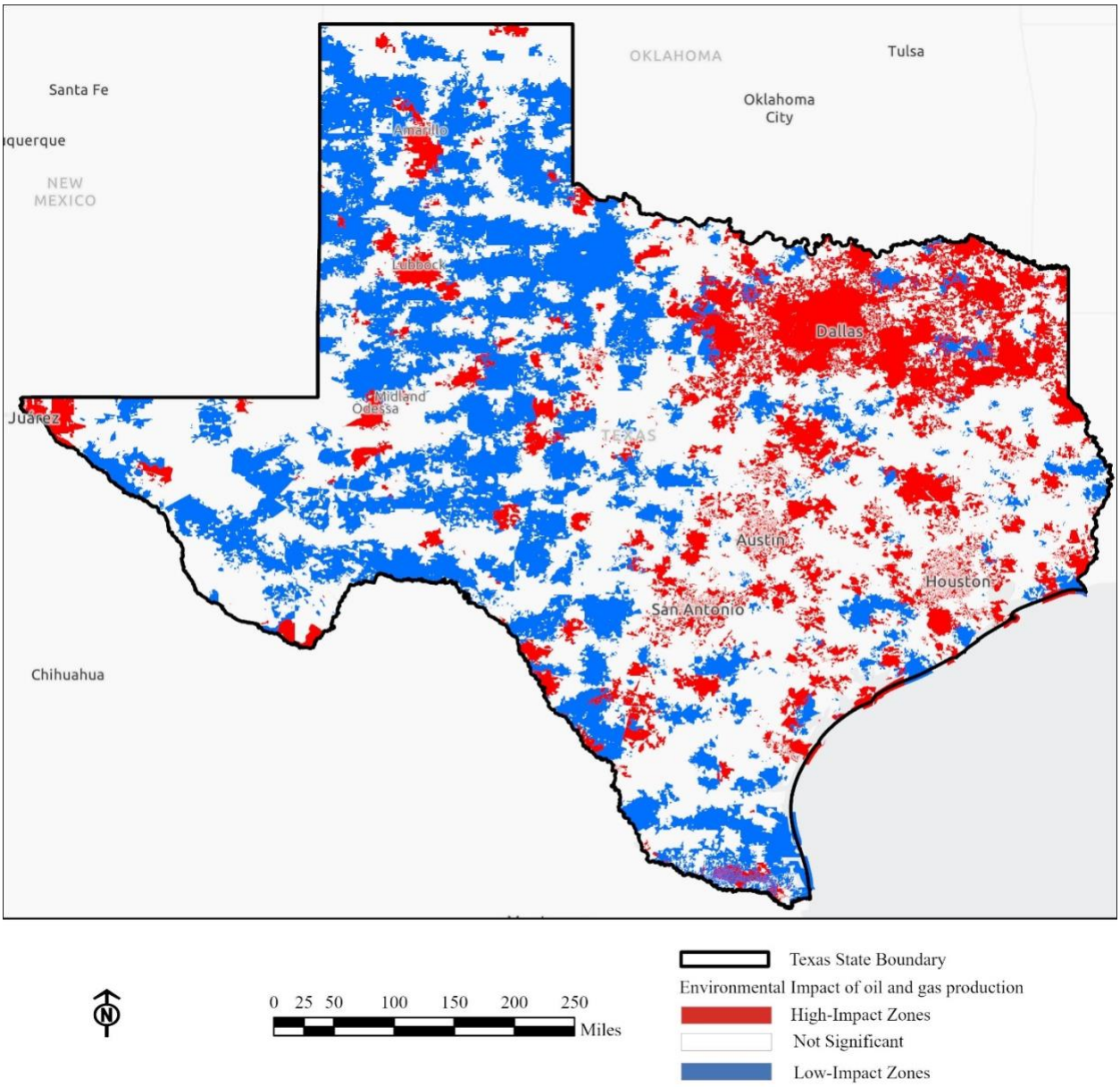


Figure 2: Getis-Ord Gi Hotspot Analysis Map Showing High-Impact, Low-Impact, and Not Significant Zones for Oil and Gas Production in Texas

Findings:

- **High-Impact Zones (Hotspots)**:
  - Major hotspots are concentrated in urban areas like **Houston**, **Dallas**, and **Austin**, similar to the optimized hotspot results. These areas have significant clustering of high sensitivity values due to the overlap of hydrographic features, sensitive land cover types (e.g., forests and wetlands), and high population densities.
  - Additional hotspots are found in South Texas along the Gulf Coast, reinforcing its ecological sensitivity due to oil and gas production near coastal wetlands.

- **Low-Impact Zones (Coldspots)**:
    - Found in rural areas, particularly in **West Texas**, where oil and gas wells are located in low-sensitivity areas with barren land and sparse human populations.
    - These regions show a lack of significant environmental or human sensitivity.
- **Not Significant Zones**:
    - Similar to the optimized hotspot analysis, areas without significant spatial clustering of environmental sensitivity values.

Interpretation:

The Getis-Ord Gi* map offers finer spatial detail and confirms the patterns observed in the optimized hotspot analysis. It highlights clusters of environmental sensitivity, providing validation and statistical robustness to the findings.

Key Comparisons Between the Maps

- **Agreement**:
    - Both maps identify similar high-impact zones, especially in urban centers and along the Gulf Coast.
    - Low-impact zones are consistently identified in West Texas, where oil and gas activities overlap with less sensitive features.
- **Differences**:
    - The Getis-Ord Gi* analysis provides more detailed, statistically validated clusters compared to the broader patterns observed in the optimized hotspot analysis.

Real-World Implications

1. **Urban Areas**:
    - High-impact zones in urban areas like **Houston**, **Austin**, and **Dallas** emphasize the need for stricter regulations and mitigation strategies for oil and gas production near densely populated and ecologically sensitive zones (Adgate et al., 2014).
2. **Coastal Regions**:
    - The Gulf Coast's high sensitivity due to wetlands and hydrographic features highlights the need for enhanced monitoring and environmental protection in this region (Mason et al., 2021).
3. **Rural Areas**:
    - Low-impact zones in rural West Texas could be considered for future development, with appropriate safeguards to maintain low sensitivity levels.

DISCUSSION

The findings from this analysis highlight critical areas in Texas where oil and gas production activities have the most significant environmental and societal impacts. The results provide a

clear understanding of spatial patterns of sensitivity and risk, which can inform policymakers, environmental managers, and industry stakeholders.

1. High-Impact Zones

High-impact zones were primarily identified in urban areas such as **Houston**, **Austin**, and **Dallas**, as well as along the **Gulf Coast**. These areas exhibit overlapping sensitive features such as wetlands, forests, and high population densities. The clustering of oil and gas wells in these regions poses significant risks to both ecosystems and human health.

Environmental Risks

- **Water Quality**: Wetlands and streams in high-impact zones are particularly vulnerable to contamination from oil spills, runoff, and industrial wastewater. Studies have shown that oil and gas activities can introduce toxic substances, including heavy metals and hydrocarbons, into nearby water systems, affecting both aquatic life and water supply for human use (Mason et al., 2021).
- **Ecosystem Damage**: Sensitive ecosystems such as forests and wetlands are crucial for biodiversity and carbon storage. Their disruption could result in habitat loss, decreased air quality, and increased greenhouse gas emissions.

Human Health Impacts

- High-impact zones in urban areas highlight potential risks to densely populated communities. Exposure to air pollution from gas flaring, methane emissions, and volatile organic compounds (VOCs) has been linked to respiratory and cardiovascular health issues (Adgate et al., 2014).
- Urban areas near oil and gas production may also face noise pollution and safety risks, such as explosions or industrial accidents.

2. Low-Impact Zones

Low-impact zones were predominantly found in rural areas of **West Texas**, where oil and gas wells are located in barren lands or regions with sparse populations and minimal hydrographic sensitivity.

Opportunities for Development

- These regions represent areas where oil and gas activities have minimal overlap with sensitive ecosystems or human populations, making them potentially more suitable for continued or expanded production.
- However, even in low-impact zones, baseline environmental monitoring is essential to prevent long-term damage from cumulative activities.

Limitations

- Low population density in these areas does not necessarily mean zero environmental impact. Studies suggest that barren lands, though less ecologically sensitive, can still face long-term degradation, such as soil erosion or aquifer contamination, from drilling activities (Vidic et al., 2013).

3. Policy Implications

The results provide actionable insights for decision-making and resource management:

1. **Targeted Mitigation in High-Impact Zones**:
    - Focus on areas like **Houston** and the **Gulf Coast**, where oil and gas production overlaps with sensitive ecosystems and human populations. Policies should prioritize stricter regulations, improved infrastructure for wastewater treatment, and enhanced monitoring systems to mitigate risks.
2. **Strategic Planning in Low-Impact Zones**:
    - Direct future oil and gas developments to low-impact zones, provided that proper safeguards are in place to prevent cumulative environmental degradation.
3. **Community Engagement**:
    - Engage local communities in high-impact zones to address their concerns and implement measures to protect public health and environmental quality.

4. Limitations of the Study

While the results provide valuable insights, several limitations must be acknowledged:

- **Static Data**: The analysis relied on datasets from specific timeframes. Land cover, population density, and oil and gas production patterns can change over time, affecting the accuracy of results.
- **Weighting Assumptions**: The weighted overlay method used subjective weights for hydrography, land cover, and population. Future studies could refine these weights by incorporating expert input or additional data.
- **Lack of Temporal Analysis**: This study did not assess how environmental sensitivity changes over time due to oil and gas activities.

5. Future Research Directions

1. **Incorporate Climate Data**:
    - Future studies could include climate-related factors, such as flood zones or drought impacts, to better understand the vulnerability of hydrographic features.

2. **Assess Cumulative Impacts**:
    - Examine how cumulative oil and gas activities over time contribute to environmental and health risks.
3. **Use Machine Learning**:
    - Advanced modeling techniques, such as machine learning, could refine hotspot analysis and identify hidden patterns in spatial relationships.

Conclusion

This study examined the environmental sensitivity of areas impacted by oil and gas production in Texas using advanced spatial analysis methods such as weighted overlay and hotspot analysis. The findings reveal that high-impact zones are primarily concentrated in urban areas like Houston, Austin, and Dallas, as well as along the Gulf Coast, where sensitive ecosystems, such as wetlands and forests, overlap with dense population centers. These areas face significant risks, including contamination of water resources, disruption of ecosystems, and public health concerns like respiratory illnesses caused by air pollution, as supported by Witter et al. (2013) (https://ehjournal.biomedcentral.com/articles/10.1186/1476-069X-12-86). In contrast, low-impact zones, predominantly located in rural West Texas, were identified as less sensitive due to barren land and sparse populations. These areas offer opportunities for sustainable development with minimal immediate environmental impact, although proper monitoring and safeguards are essential to avoid cumulative degradation, as emphasized by Vidic et al. (2013) (https://pubs.acs.org/doi/10.1021/es402165b). The results underscore the importance of targeted mitigation strategies in high-impact zones, such as stricter regulations, enhanced wastewater management, and proactive monitoring of air and water quality, while promoting responsible development in low-impact areas. Despite the insights provided, this analysis is based on static data, and future research should incorporate temporal trends to evaluate the long-term effects of oil and gas production. Additionally, incorporating climate data, such as flood risks, and engaging local communities in decision-making processes will further refine land-use planning and environmental policies. Overall, this study highlights the critical need to balance energy production with environmental sustainability by prioritizing resource management in high-risk areas and promoting sustainable practices in regions with lower sensitivity.

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ANNEX

Annex 1: Reclassification Table for NLCD

NLCD Code	Land Cover Class	Reclassification Rank	Justification
11	Open Water	**8**	Oil and gas activities can lead to water contamination; water bodies are highly sensitive.
12	Perennial Ice/Snow	**N/A**	Likely not present in Texas; can be excluded from the analysis.
21	Developed, Open Space	**4**	These areas typically have lower environmental sensitivity, but impacts on recreational use are possible.
22	Developed, Low Intensity	**3**	Suburban or low-density housing areas with some potential for human impact.
23	Developed, Medium Intensity	**2**	Urban areas where the environment is already modified; less direct ecological sensitivity.
24	Developed, High Intensity	**1**	Dense urban areas are less environmentally sensitive due to existing infrastructure.
31	Barren Land	**2**	Low sensitivity due to minimal ecological value, but can be impacted by erosion or dust.
41	Deciduous Forest	**10**	Highly sensitive due to biodiversity and ecosystem services.
42	Evergreen Forest	**10**	Evergreen forests are critical for ecosystem stability and are sensitive to disruption.
43	Mixed Forest	**10**	Forests with diverse ecosystems are highly sensitive.
52	Shrub/Scrub	**6**	Moderately sensitive; impacts include habitat loss and erosion.
71	Grassland/Herbaceous	**7**	Grasslands provide habitat and erosion control, making them moderately sensitive.

NLCD Code	Land Cover Class	Reclassification Rank	Justification
81	Pasture/Hay	**5**	Agricultural areas have moderate sensitivity; contamination of soil and water can affect productivity.
82	Cultivated Crops	**4**	Farmland is less sensitive ecologically but can suffer from contamination and productivity loss.
90	Woody Wetlands	**10**	Wetlands are highly sensitive due to their ecological importance (e.g., water filtration, habitats).
95	Emergent Herbaceous Wetlands	**10**	Wetlands are extremely sensitive and require protection from contamination and habitat destruction.

Annex 2: Reclassification Scheme for Population Raster

Population Range (people per cell)	Reclassification Value (Rank)	Justification
0	**1**	No population; no human impact expected.
1–100	**2**	Very low population density; minimal sensitivity.
101–300	**4**	Low population density; minor potential for human impact.
301–600	**6**	Moderate population density; noticeable impacts likely.
601–1000	**8**	High population density; significant risk of human impact.
1001–1613	**10**	Very high population density; most sensitive to environmental risks.

Annex 3: Reclassification Table for NHD FCode

FCode	Feature Description	Reclassification Value	Justification
31200	Stream/River	**8**	Important hydrological features susceptible to pollution and sedimentation.
33600	Pipeline	**3**	Artificial structures with minimal environmental sensitivity.
34300	Canal/Ditch	**4**	Moderately important; artificial and primarily functional.
34305	Aqueduct	**4**	Artificial water conveyance; less ecologically sensitive.
36100	Connector	**2**	Artificial connections with limited environmental significance.
36400	Dam/Weir	**5**	Human-made structures with localized impacts on water flow.
39000	Artificial Path	**6**	Important for hydrological flow but artificial in nature.
39001	Stream/River (Perennial)	**9**	Critical water features, highly sensitive to contamination and disruption.
39004	Stream/River (Ephemeral)	**7**	Seasonal water features, moderately sensitive but essential for ecosystems.
39005	Stream/River (Intermittent)	**7**	Similar sensitivity to ephemeral streams.
39006	Braided Stream	**8**	Highly sensitive due to complex hydrological and ecological interactions.

39009	Intermittent Streams	**7**	Seasonally important for water flow and habitats.
39010	Natural Channel	**8**	Natural hydrological systems sensitive to disruption.
39011	Canal/Artificial Channel	**5**	Artificial but with some hydrological significance.
39012	Conveyance (Non-Flowing)	**3**	Functional and artificial; low sensitivity.
40307	Lock Chamber	**2**	Artificial; minimal ecological impact.
40308	Fish Ladder	**6**	Artificial but supports aquatic ecosystems; moderately sensitive.
40309	Spillway	**5**	Artificial water management; less ecological sensitivity.
43600	Reservoir	**8**	Important for water supply but less sensitive than natural water bodies.
43601	Water Impoundment	**7**	Moderately sensitive, primarily functional.
43604	Water Retention Basin	**6**	Artificial, with moderate environmental relevance.
43606	Detention Basin	**5**	Artificial; low ecological sensitivity.
43610	Excavated Waterbody	**4**	Artificial, minimal sensitivity.
43612	Sewage Treatment Lagoon	**3**	Artificial with low environmental sensitivity.
43613	Water Storage Basin	**4**	Artificial, primarily functional.
43614	Cooling Pond	**4**	Artificial, industrial use, minimal sensitivity.

43615	Industrial Pond	**3**	Low sensitivity, primarily artificial.
43618	Mine Tailings Pond	**3**	Artificial with potential contamination concerns but low ecological value.
43619	Wastewater Treatment Pond	**3**	Artificial, low sensitivity but some contamination risk.
43624	Settling Pond	**4**	Artificial, moderate relevance due to potential contamination risks.
43625	Tailing Pond	**3**	Artificial, similar to mine tailings ponds.
44500	Bay/Estuary	**10**	Extremely sensitive ecosystems, critical for biodiversity and hydrology.
45500	Ocean	**9**	High sensitivity due to ecological and hydrological importance.
46003	Glacier	**N/A**	Likely not present in Texas; can be excluded.
46006	Swamp/Marsh	**10**	Highly sensitive wetland areas critical for ecosystems and water filtration.
46100	Perennial Lake/Pond	**9**	Essential for ecosystems, highly sensitive to contamination.
46600	Wetlands	**10**	Extremely sensitive areas critical for biodiversity and hydrological health.
46601	Non-Perennial Wetlands	**9**	Highly sensitive but seasonally affected.
48400	Ice Mass	**N/A**	Likely not relevant in Texas; can be excluded.

49300	Playa	**6**	Semi-arid features, moderately sensitive due to limited ecological importance