International Journal of Scientific Research and Modern Technology (IJSRMT) ijsrmt.com
Volume 4, Issue 10, 2025
DOI: https://doi.org/10.38124/ijsrmt.v4i10.1285

Automated FEMA-Compliant Floodplain Encroachment Assessment Using Python-Based Geospatial Workflows

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Publication Date: 2025/10/30

Abstract

Increasing flood risks driven by climate variability and expanding urban development have intensified the need for efficient and consistent floodplain compliance assessment methods. This study presents an automated FEMA-compliant floodplain encroachment assessment framework developed using Python-based geospatial workflows to improve regulatory evaluation processes. The proposed system integrates Digital Elevation Models, FEMA Flood Insurance Rate Maps, floodway boundaries, land parcel datasets, and hydraulic model outputs within a unified computational pipeline. Automated spatial overlay operations, buffer analysis, and elevation threshold comparisons were implemented to detect encroachments and classify structures as compliant or non-compliant according to FEMA regulatory criteria, including Base Flood Elevation validation and no-rise requirements. Results demonstrate that automation significantly reduces processing time compared to traditional manual GIS workflows while maintaining high agreement with regulatory assessment outcomes. Spatial compliance mapping revealed clustering of violations along river corridors and low-lying development zones, providing actionable insights for planners and floodplain managers. The workflow enhances reproducibility by encoding regulatory logic into programmable scripts, enabling consistent reassessment under updated datasets or evolving flood hazard conditions. Performance evaluation confirms improved analytical efficiency, standardized decision-making, and scalability suitable for broader regional or national implementation. Practical implications include integration into municipal permitting systems, improved decision-support for regulatory agencies, and potential for real-time compliance monitoring. Although limitations related to data quality, hydraulic modeling uncertainty, and regulatory interpretation remain, the study demonstrates that automated geospatial analysis can substantially modernize floodplain management practices. The framework establishes a scalable foundation for future integration with cloud geospatial platforms, machine learning–based flood prediction systems, and standardized compliance APIs, supporting resilient infrastructure planning and transparent flood risk governance.

Keywords: *Floodplain Encroachment Assessment; FEMA Compliance; Geospatial Automation; Python-Based GIS; Flood Risk Management.*

I. INTRODUCTION

➢ *Background and Problem Context*

Flood hazards have intensified globally due to the combined effects of climate variability, land-use transformation, and rapid urban expansion into historically flood-prone areas. Increasing precipitation extremes, altered hydrological cycles, and watershed modification have significantly amplified flood frequency and magnitude, placing growing pressure on flood risk management systems and infrastructure planning (IPCC, 2021; Wing et al., 2022). Urban development within floodplains further exacerbates vulnerability by increasing impervious surfaces, accelerating runoff, and reducing

Isibor, I., Bamigwojo, O. V., Enyejo, L., & Olola, G. I. (2025). Automated FEMA-Compliant Floodplain Encroachment Assessment Using Python-Based Geospatial Workflows. *International Journal of Scientific Research and Modern Technology*, *4*(10), 225–244.
https://doi.org/10.38124/ijsrmt.v4i10.1285

natural flood storage capacity, thereby elevating downstream flood risks (Tellman et al., 2021). As a result, accurate floodplain assessment has become a critical component of sustainable urban planning and disaster mitigation strategies.

Within the United States, the Federal Emergency Management Agency (FEMA) establishes regulatory standards governing floodplain development through the National Flood Insurance Program (NFIP), which requires strict evaluation of floodway encroachments to ensure that proposed developments do not increase base flood elevations or compromise hydraulic conveyance capacity (FEMA, 2020). Floodplain encroachment analysis is therefore essential in hydraulic engineering and permitting processes, where planners must verify compliance using Flood Insurance Rate Maps (FIRMs), hydraulic models, and elevation datasets (Maidment, 2017). These regulatory assessments play a central role in minimizing flood damage, protecting communities, and maintaining eligibility for federal insurance programs.

Despite their importance, traditional floodplain compliance evaluations rely heavily on manual Geographic Information System (GIS) workflows involving repetitive spatial overlays, elevation comparisons, and regulatory interpretation. Such manual procedures are time-consuming, prone to subjective decision-making, and difficult to reproduce consistently across jurisdictions (Zhu et al., 2019). The increasing availability of high-resolution geospatial data has further intensified computational demands, making manual approaches inefficient for large-scale or frequently updated assessments (Li & Gong, 2022). Moreover, fragmented datasets distributed across hydraulic modeling platforms, cadastral databases, and regulatory repositories often require extensive preprocessing before analysis can begin.

Recent advances in geospatial automation and open-source programming environments offer a pathway toward addressing these limitations. Python-based geospatial libraries enable automated spatial analysis, reproducible workflows, and scalable processing of large environmental datasets, thereby supporting standardized regulatory evaluation (Rey et al., 2023). Automation enhances transparency by embedding regulatory rules directly into computational pipelines, reducing human error while enabling rapid scenario testing and regulatory auditing (Anselin et al., 2022). Automated workflows also facilitate integration between flood modeling outputs and compliance verification systems, allowing planners to transition from static mapping practices toward dynamic, data-driven floodplain management.

Consequently, there is an increasing need for automated, reproducible, and scalable geospatial frameworks capable of performing FEMA-compliant floodplain encroachment assessments. Developing such systems can significantly improve regulatory efficiency, enhance decision support for hydraulic planners, and support resilient infrastructure development under evolving climate conditions.

Figure 1 illustrates the integrated architecture of the automated floodplain encroachment assessment system, showing how multiple geospatial datasets are transformed into regulatory decision outputs. Input layers, including Digital Elevation Models, FEMA FIRM maps, hydraulic model outputs, and parcel data, feed into a FEMA compliance rule layer that encodes regulatory requirements such as Base Flood Elevation and no-rise criteria. These datasets are processed through a Python-based geospatial engine that automates spatial analysis and compliance evaluation. The workflow converts complex spatial and hydraulic information into actionable outputs, including encroachment maps, compliance reports, and decision dashboards. Overall, the figure demonstrates how automation links raw geospatial data with transparent, standardized regulatory decision-making.

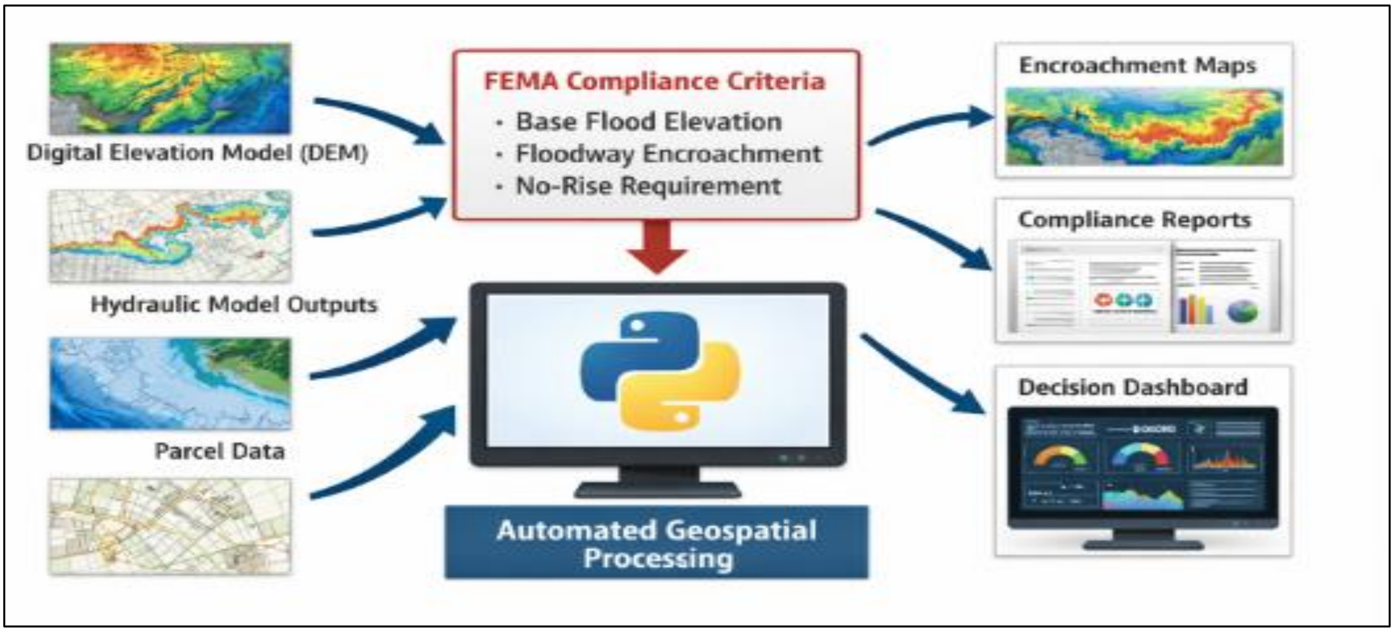

Fig 1 Conceptual System Overview of Automated FEMA-Compliant Floodplain Encroachment Assessment

- *Research Motivation*

Floodplain management professionals and hydraulic engineers increasingly face complex technical and regulatory challenges when conducting FEMA compliance verification for proposed developments within regulated flood zones. The evaluation of floodplain encroachments requires precise interpretation of hydraulic impacts, spatial boundary conditions, and elevation constraints defined under FEMA's National Flood Insurance Program (NFIP). In practice, planners must determine whether infrastructure projects alter flood conveyance capacity or increase Base Flood Elevations (BFEs), tasks that demand careful integration of hydraulic modeling outputs with spatial datasets. These processes are often labour-intensive and depend heavily on manual GIS operations, increasing the likelihood of inconsistencies across jurisdictions and introducing delays in permitting decisions. As flood risks intensify and development pressures expand into vulnerable areas, regulatory agencies require faster yet technically reliable compliance verification mechanisms.

A major obstacle in FEMA-compliant assessments arises from data fragmentation. Floodplain analyses typically rely on multiple heterogeneous datasets, including Digital Elevation Models (DEMs) for terrain representation, FEMA Flood Insurance Rate Maps (FIRMs) for regulatory boundaries, hydraulic simulation outputs such as HEC-RAS water surface profiles, and cadastral parcel datasets defining property extents. These datasets are produced using different coordinate systems, spatial resolutions, and data formats, requiring extensive preprocessing before meaningful analysis can occur. Engineers frequently spend substantial effort harmonizing projections, cleaning geometries, and reconciling attribute schemas rather than performing analytical evaluation. The absence of standardized integration workflows limits reproducibility and makes it difficult to maintain audit-ready documentation for regulatory review. Furthermore, updates to floodplain maps or terrain data often require analysts to repeat entire workflows manually, reducing operational efficiency and scalability.

Recent developments in Python-based geospatial ecosystems present a compelling opportunity to address these limitations. Open-source libraries such as GeoPandas, Rasterio, Shapely, and PyProj enable automated spatial processing, allowing regulatory logic to be embedded directly into computational workflows. Through scripting and workflow automation, repetitive GIS tasks can be standardized, reducing human error while improving analytical transparency. Python environments also support integration with hydraulic modeling outputs, enabling automated comparison between terrain elevations, floodway boundaries, and regulatory thresholds. Beyond efficiency gains, automated workflows promote reproducibility, allowing planners and agencies to document analytical steps programmatically and reproduce compliance decisions under changing datasets or regulatory updates.

The motivation for this research therefore emerges from the intersection of regulatory complexity, fragmented geospatial data environments, and the growing availability of programmable geospatial tools. By leveraging Python-based automation, FEMA floodplain encroachment assessments can transition from manual, case-specific analyses toward scalable, transparent, and repeatable computational frameworks capable of supporting modern flood risk governance and resilient infrastructure planning.

- *Research Objectives*

The increasing complexity of floodplain management and regulatory compliance processes necessitates the development of analytical frameworks capable of improving accuracy, efficiency, and consistency in floodplain encroachment assessment. Traditional evaluation approaches rely heavily on manual interpretation of spatial datasets and engineering judgment, which may introduce variability in outcomes and limit scalability across multiple jurisdictions. In response to these challenges, this study establishes a set of research objectives aimed at advancing automated, standards-compliant geospatial assessment methodologies for FEMA-regulated floodplains.

The first objective is to develop an automated encroachment detection workflow using Python-based geospatial tools. The proposed workflow is designed to integrate terrain elevation data, regulatory floodplain boundaries, hydraulic modeling outputs, and parcel-level spatial information into a unified analytical pipeline. Automated spatial operations, including overlay analysis, buffering, elevation comparison, and rule-based classification, will be implemented to systematically identify potential floodplain and floodway encroachments. By embedding analytical logic within programmable scripts, the workflow seeks to eliminate repetitive manual GIS procedures while enabling rapid processing of large geospatial datasets.

The second objective is to ensure conformity with FEMA regulatory requirements governing floodplain development. FEMA compliance assessments require verification that proposed developments do not increase base flood elevations or obstruct floodway conveyance capacity. This research aims to encode FEMA regulatory criteria into computational rules that can automatically evaluate compliance conditions. Translating regulatory guidelines into algorithmic logic allows for consistent interpretation of standards and supports transparent auditing of analytical decisions during permitting and planning processes.

A third objective is to reduce analysis time and minimize subjective interpretation associated with manual compliance evaluations. Automated geospatial processing enables standardized execution of analytical steps, thereby reducing dependence on individual analyst experience and decreasing the potential for inconsistent results. Streamlined workflows are expected to significantly shorten assessment timelines while maintaining technical rigor required for hydraulic and regulatory review.

Finally, the study aims to enable reproducible floodplain assessments through the adoption of script-based geospatial computation. Reproducibility ensures that analyses can be repeated under updated datasets, alternative development scenarios, or revised regulatory conditions without reconstructing workflows from scratch. By promoting transparency, repeatability, and scalability, the proposed framework supports evidence-based floodplain management and enhances decision-making capabilities for planners, engineers, and regulatory agencies.

- *Contributions of the Study*

This study contributes to the advancement of computational floodplain management by introducing an automated, regulation-oriented framework for FEMA-compliant floodplain encroachment assessment. As flood risk analysis increasingly depends on large and heterogeneous geospatial datasets, there is a growing need for analytical systems capable of integrating regulatory requirements directly into spatial computation. The contributions of this research are therefore centered on methodological innovation, regulatory automation, and practical decision-support enhancement for engineering and planning applications.

The primary contribution is the development of a Python-based FEMA compliance engine that operationalizes regulatory floodplain evaluation within a programmable geospatial environment. Unlike traditional GIS workflows that rely on manual interpretation and sequential processing, the proposed engine embeds FEMA compliance logic into automated scripts capable of systematically analysing spatial relationships between development footprints and regulated floodplain zones. By leveraging open-source geospatial libraries, the system enables scalable processing of terrain models, flood boundary datasets, and hydraulic outputs while maintaining transparency and reproducibility. This approach transforms regulatory assessment from a document-driven procedure into a computationally verifiable process.

A second contribution involves the implementation of automated spatial intersection and hydraulic constraint evaluation. The study introduces algorithmic procedures that perform spatial overlays, elevation comparisons, and rule-based validation to determine whether proposed developments violate floodway encroachment limits or hydraulic performance criteria. Automated intersection analysis allows rapid identification of structures located within restricted zones, while encoded hydraulic constraints enable systematic evaluation of potential impacts on base flood elevations. This integration bridges the long-standing gap between hydraulic modeling outputs and regulatory GIS analysis, ensuring that compliance verification is both technically rigorous and operationally efficient.

The third contribution lies in generating decision-support outputs tailored for planners and regulatory agencies. The automated workflow produces standardized outputs, including compliance classification maps, encroachment reports, and spatial risk visualizations that facilitate informed decision-making. These outputs enhance communication between engineers, planners, and permitting authorities by presenting analytical results in interpretable and audit-ready formats. By reducing ambiguity in compliance interpretation and enabling rapid scenario evaluation, the framework supports proactive planning strategies and improves the efficiency of floodplain management processes.

Collectively, these contributions demonstrate how programmable geospatial workflows can modernize FEMA compliance assessment, promote consistency across regulatory evaluations, and provide scalable analytical tools for resilient infrastructure planning in flood-prone environments.

II. LITERATURE REVIEW

- *FEMA Floodplain Regulations and Encroachment Analysis*

Floodplain regulation in the United States is primarily governed by the Federal Emergency Management Agency (FEMA) through the National Flood Insurance Program (NFIP), which establishes standards for land development within flood-prone areas to minimize flood damage and protect public safety. The regulatory framework distinguishes between the broader floodplain, commonly defined by the 1% annual chance flood (100-year flood), and the floodway, which represents the channel and adjacent land areas required to convey floodwaters without substantially increasing water surface elevations (FEMA, 2020). Development within these zones is strictly controlled to ensure that human activities do not exacerbate flood hazards or transfer risk to surrounding communities.

A central principle of FEMA floodplain management is the no-rise requirement, which mandates that any proposed development within a designated floodway must demonstrate, typically through hydraulic modeling, that it will not increase the Base Flood Elevation (BFE). This requirement necessitates technical analyses integrating hydrologic data, hydraulic simulations, and geospatial mapping to evaluate encroachment impacts (Maidment, 2017). Regulatory enforcement relies heavily on Flood Insurance Rate Maps (FIRMs), hydraulic studies, and engineering certifications that verify compliance before construction permits are granted. These measures aim to preserve flood conveyance capacity while maintaining eligibility for federal flood insurance programs.

Existing compliance assessment methodologies typically combine hydraulic modeling tools such as HEC-RAS with Geographic Information System (GIS) analysis. Engineers evaluate floodplain encroachments by comparing proposed development footprints against mapped regulatory boundaries and simulated flood elevations (Merwade et al., 2008). While effective, these processes often involve manual spatial analysis and iterative validation, requiring significant technical expertise and time investment. Studies have shown that manual workflows may introduce inconsistencies due to variations in data preprocessing, projection handling, and interpretation of regulatory thresholds (Zhang & Li, 2021).

Furthermore, the increasing availability of high-resolution terrain datasets and frequently updated flood hazard maps has expanded analytical complexity. Traditional compliance workflows struggle to efficiently integrate multiple datasets, including Digital Elevation Models (DEMs), parcel boundaries, and hydraulic outputs, leading to fragmented assessment procedures (Sampson et al., 2015). As regulatory agencies face growing development pressure and climate-driven flood risks, there is a recognized need for standardized and automated compliance assessment mechanisms capable of improving efficiency and transparency (Kumar et al., 2020).

Recent research emphasizes the importance of integrating computational workflows into floodplain management to enhance reproducibility and regulatory consistency. Automated geospatial approaches enable systematic encoding of regulatory rules, reducing subjective interpretation and supporting audit-ready analysis (Goodchild, 2018). Such approaches align with FEMA's broader objective of modernizing flood hazard mapping and improving risk-informed planning through data-driven methodologies (FEMA, 2020). Consequently, advancing automated encroachment assessment frameworks represents a logical evolution of FEMA compliance practices within contemporary geospatial engineering environments.

Figure 2 illustrates the structured regulatory process followed during FEMA floodplain encroachment evaluation, beginning with permit application submission and progressing through technical review stages. The workflow integrates data collection, hydraulic and geospatial analysis, and no-rise certification assessment to ensure developments do not increase flood risk. Each stage represents a decision checkpoint where engineering and regulatory requirements are verified systematically. The final branch distinguishes compliant projects from those requiring revision, emphasizing regulatory accountability. Overall, the figure demonstrates a sequential and transparent compliance pathway that supports consistent floodplain management decisions.

Fig 2 FEMA Floodplain Encroachment Regulatory Workflow

➢ *GIS-Based Floodplain Mapping Techniques*

Geographic Information Systems (GIS) play a central role in floodplain mapping and flood risk assessment by enabling spatial visualization, terrain analysis, and integration of hydrological datasets. Traditional GIS workflows for floodplain analysis typically involve manual processing steps such as terrain preprocessing, spatial overlay operations, and flood boundary delineation. Analysts commonly integrate topographic datasets, hydrological features, and regulatory flood maps to produce inundation extents and hazard classifications. These workflows rely heavily on desktop GIS platforms where users sequentially execute geoprocessing tools, often requiring substantial technical expertise and manual validation at each stage (de Smith et al., 2018). While effective for localized studies, traditional workflows may become inefficient when applied to large datasets or repeated regulatory assessments due to their limited automation and reproducibility.

Digital Elevation Models (DEMs) form the foundational dataset for modern floodplain mapping because terrain elevation strongly influences water flow paths, flood depth, and inundation extent. DEM-based flood modeling uses elevation data to derive hydrological parameters such as flow direction, watershed boundaries, and flood storage capacity. High-resolution DEMs derived from LiDAR technology have significantly improved the accuracy of flood simulations by capturing fine-scale terrain variations that influence flood propagation (Sampson et al., 2015). GIS-based terrain analysis enables the generation of flood inundation surfaces through elevation thresholding and raster-based hydrological modeling, supporting preliminary flood risk assessments and spatial planning decisions (Wilson & Gallant, 2000). However, DEM-only approaches may oversimplify hydraulic dynamics when channel flow behaviour and infrastructure interactions are not explicitly modelled.

To address these limitations, hydraulic models such as the Hydrologic Engineering Center's River Analysis System (HEC-RAS) are widely integrated with GIS environments. HEC-RAS simulates water surface profiles using hydraulic equations that account for channel geometry, roughness coefficients, and flow conditions. The integration of HEC-RAS outputs with GIS platforms allows analysts to spatially visualize flood extents, depth grids, and velocity distributions, thereby enhancing floodplain delineation accuracy (Brunner, 2016). GIS tools are used to convert hydraulic simulation outputs into geospatial layers that can be compared with land-use data, infrastructure footprints, and regulatory boundaries. This coupling between hydraulic modeling and GIS analysis provides a comprehensive framework for evaluating floodplain encroachments and assessing regulatory compliance.

Despite these advancements, challenges remain in synchronizing GIS and hydraulic workflows due to differences in data formats, coordinate systems, and preprocessing requirements. Manual transfer of datasets between modeling environments can introduce errors and reduce analytical efficiency. Consequently, recent research emphasizes the importance of automated geospatial workflows capable of seamlessly integrating DEM processing, hydraulic simulation outputs, and spatial analysis within unified computational frameworks. Such integration enhances consistency in floodplain mapping while supporting scalable and repeatable assessment processes required for modern flood risk management.

- *Automation in Geospatial Analysis*

The rapid growth of geospatial data availability has driven the need for automated analytical approaches capable of efficiently processing large spatial datasets while ensuring analytical consistency. Automation in geospatial analysis refers to the use of programmable environments to execute spatial operations, data transformations, and analytical workflows without repeated manual intervention. Python has emerged as one of the most influential programming languages in this domain due to its extensive ecosystem of open-source libraries designed specifically for spatial data processing and scientific computation (Rey et al., 2023). By enabling script-based execution of geospatial tasks, automation improves efficiency, reduces human error, and enhances transparency in environmental and regulatory analyses.

Several Python libraries have become foundational tools for spatial analysis workflows. GeoPandas extends the functionality of traditional pandas data structures to support vector-based geospatial operations, allowing analysts to perform spatial joins, overlays, and attribute manipulations using familiar data science paradigms (Jordahl et al., 2020). Shapely provides geometric computation capabilities, enabling precise manipulation of spatial features such as intersections, buffering, and topology validation, which are essential for encroachment detection and boundary analysis (Gillies, 2013). For raster-based datasets, Rasterio facilitates efficient reading, writing, and transformation of geospatial raster data, including Digital Elevation Models used in floodplain assessments (Mapbox, 2021). Additionally, PyProj supports coordinate reference system transformations and geodetic calculations, ensuring spatial alignment among datasets originating from different projections or mapping standards (Snow et al., 2020).

The integration of these libraries enables the construction of automated geospatial pipelines in which data ingestion, preprocessing, spatial analysis, and output generation occur within a unified computational framework. Such automation significantly improves reproducibility, a critical requirement in scientific and regulatory environments where analytical results must be verifiable and repeatable. Reproducible geospatial pipelines document every analytical step through executable scripts, allowing analysts to rerun workflows using updated datasets or modified parameters without reconstructing processes manually (Anselin et al., 2022). This capability is particularly valuable for floodplain compliance analysis, where regulatory decisions must remain transparent and defensible.

Automated geospatial workflows also facilitate modular system architectures that separate data handling, processing logic, analytical evaluation, and visualization outputs. This layered structure enhances scalability and supports integration with cloud computing platforms and decision-support systems. As geospatial analysis increasingly intersects with data science and environmental modeling, Python-based automation frameworks provide a robust foundation for developing standardized analytical systems capable of addressing complex spatial regulatory challenges.

Figure 3 presents a layered software architecture illustrating how automated geospatial analysis is structured from raw data acquisition to decision-support outputs. The data layer forms the foundation by integrating DEMs, FEMA FIRMs, hydraulic models, and parcel datasets required for regulatory assessment. The processing layer standardizes and transforms spatial data using Python libraries, ensuring interoperability across datasets. The analysis layer applies spatial logic and encoded FEMA compliance rules to evaluate encroachments systematically. Finally, the visualization layer converts analytical results into compliance maps, reports, and dashboards that support planning and regulatory decision-making.

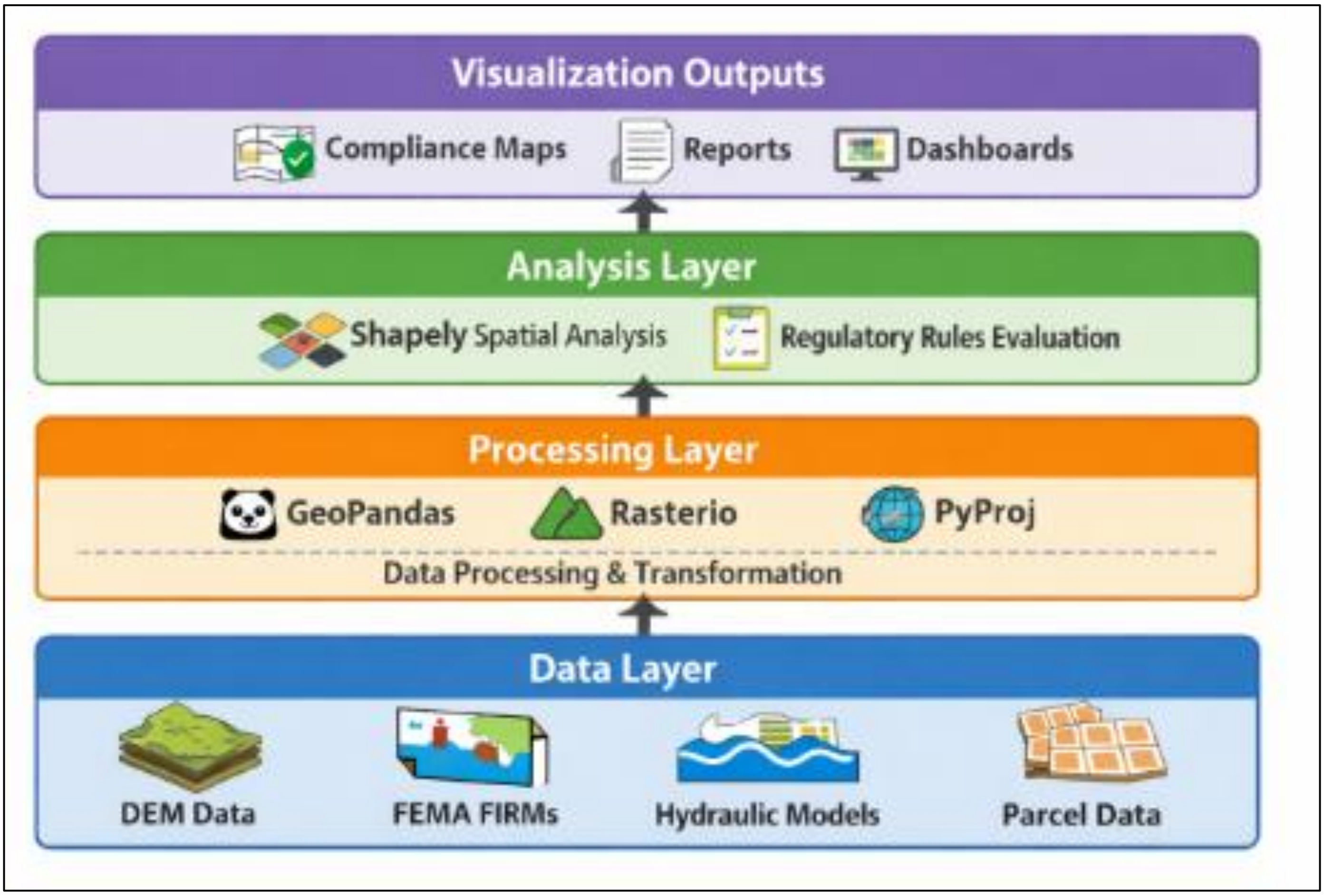

Fig 3 Layered Software Architecture for Automated Geospatial Analysis

- *Research Gaps*

Despite substantial advancements in floodplain mapping, hydraulic modeling, and geospatial analysis, significant gaps remain in the development of standardized tools capable of automating FEMA-compliant floodplain encroachment assessments. Existing flood risk evaluation frameworks primarily emphasize hazard mapping and hydraulic simulation rather than regulatory compliance automation. FEMA guidelines provide detailed procedural requirements for floodplain evaluation; however, the implementation of these requirements is typically left to individual agencies or consulting engineers, resulting in inconsistent analytical approaches across jurisdictions (FEMA, 2020). The absence of standardized automated compliance systems creates variability in interpretation, increases review time, and complicates auditability of regulatory decisions.

One major research gap is the lack of standardized automated FEMA compliance tools capable of translating regulatory policies into computational workflows. Current practices rely heavily on manual GIS operations combined with engineering judgment, which can introduce subjective interpretation during encroachment assessment and no-rise certification processes. Studies in geospatial science have highlighted that many environmental regulatory analyses still depend on semi-manual procedures, limiting reproducibility and hindering large-scale deployment of compliance evaluation systems (Goodchild, 2018). While automation has advanced in hazard modeling, regulatory decision logic remains largely unencoded within analytical platforms.

A second limitation involves the restricted integration between hydraulic modeling outputs and regulatory verification processes. Hydraulic models such as HEC-RAS generate detailed water surface elevation and flood depth outputs, yet these datasets often require manual conversion before being incorporated into GIS-based compliance analyses. The separation between hydraulic simulation environments and spatial regulatory assessment workflows introduces inefficiencies and increases the risk of data misalignment or analytical inconsistencies (Merwade et al., 2008). Researchers have emphasized the need for integrated systems capable of directly linking hydraulic results with spatial compliance checks to support accurate floodplain management (Kumar et al., 2020).

Additionally, there is a growing demand for scalable geospatial workflows capable of processing expanding volumes of high-resolution terrain and flood hazard data. Advances in remote sensing and LiDAR-derived Digital Elevation Models have significantly increased data availability, but many existing floodplain assessment workflows are not designed to handle repeated large-scale analyses efficiently (Sampson et al., 2015). As climate change accelerates flood risk dynamics and necessitates frequent updates to hazard maps, scalable automation becomes essential for maintaining timely and consistent regulatory evaluations.

Collectively, these gaps highlight the need for integrated, automated, and scalable geospatial frameworks that operationalize FEMA regulatory requirements within programmable analytical environments. Addressing these limitations forms the foundation of the present study, which seeks to bridge hydraulic modeling, regulatory compliance, and automated spatial analysis into a unified workflow capable of supporting modern floodplain governance.

III. METHODOLOGY

➢ *Study Area and Dataset Description*

The methodological framework for automated FEMA-compliant floodplain encroachment assessment relies on the integration of multiple geospatial and hydraulic datasets representing terrain characteristics, regulatory flood boundaries, and land development information. The study area is defined as a riverine floodplain region subject to FEMA regulatory oversight, where flood risk management and development permitting require detailed spatial analysis. The selection of datasets reflects the technical requirements necessary for evaluating floodplain encroachment conditions and ensuring regulatory compliance through spatial and hydraulic verification.

A Digital Elevation Model (DEM) serves as the primary terrain dataset used to represent ground elevation across the study area. DEMs provide the elevation surface required for hydrological and hydraulic analysis, enabling the identification of flow paths, flood storage areas, and terrain gradients influencing flood propagation. High-resolution elevation data derived from LiDAR surveys are particularly valuable for floodplain assessment because they capture subtle topographic variations that significantly affect inundation extents and water surface behaviour. The DEM is preprocessed to remove artifacts, ensure vertical datum consistency, and support spatial alignment with other datasets used in the analysis.

The second critical dataset consists of FEMA Flood Insurance Rate Maps (FIRMs), which define regulatory flood hazard zones, including Special Flood Hazard Areas (SFHAs) and base flood elevations. FIRMs provide legally recognized floodplain boundaries that guide development restrictions and insurance requirements. These maps are incorporated as vector layers representing regulatory zones against which proposed developments are evaluated. The integration of FIRMs allows automated workflows to determine whether structures intersect regulated floodplain areas and whether compliance analysis is required.

Floodway boundary datasets are included to identify areas where development restrictions are most stringent. Floodways represent portions of the floodplain reserved for the efficient conveyance of floodwaters without increasing flood elevations. Encroachment analysis focuses heavily on these zones because FEMA regulations require demonstration that proposed activities produce no measurable increase in flood levels. Floodway polygons are spatially analyzed alongside elevation and hydraulic datasets to determine potential regulatory violations.

The methodology further incorporates land parcel datasets, which provide cadastral information defining property boundaries, land ownership divisions, and development footprints. Parcel data enable localized assessment of encroachment impacts by linking regulatory flood zones to specific development units. Attribute information associated with parcels supports classification of compliance status and facilitates reporting outputs relevant to planners and permitting authorities.

Finally, hydraulic model outputs, typically generated using HEC-RAS simulations, are integrated into the workflow to represent modelled water surface elevations and flood depths under base flood conditions. These outputs provide the hydraulic context necessary for evaluating whether development activities alter flood behaviour. Raster or vector outputs derived from hydraulic simulations are spatially aligned with DEM and regulatory datasets to enable automated comparison between terrain elevations, flood extents, and regulatory thresholds.

The combination of these datasets establishes a comprehensive geospatial foundation for automated floodplain encroachment assessment. Data harmonization procedures, including coordinate system standardization and spatial resolution alignment, ensure interoperability among datasets and support accurate analytical results within the automated workflow.

Figure 4 presents the spatial extent of the study area, highlighting FEMA-designated 100-year floodplain zones and regulated floodways along the primary river corridor. The map illustrates how flood-prone regions closely follow the river and tributary network, intersecting multiple municipal boundaries within the administrative extent. Terrain shading provides elevation context, showing that floodplain areas correspond predominantly to low-lying valleys. The visualization supports encroachment analysis by clearly identifying zones where development activities are subject to regulatory review. Overall, the figure establishes the geographic and regulatory framework used for automated FEMA-compliant floodplain assessment.

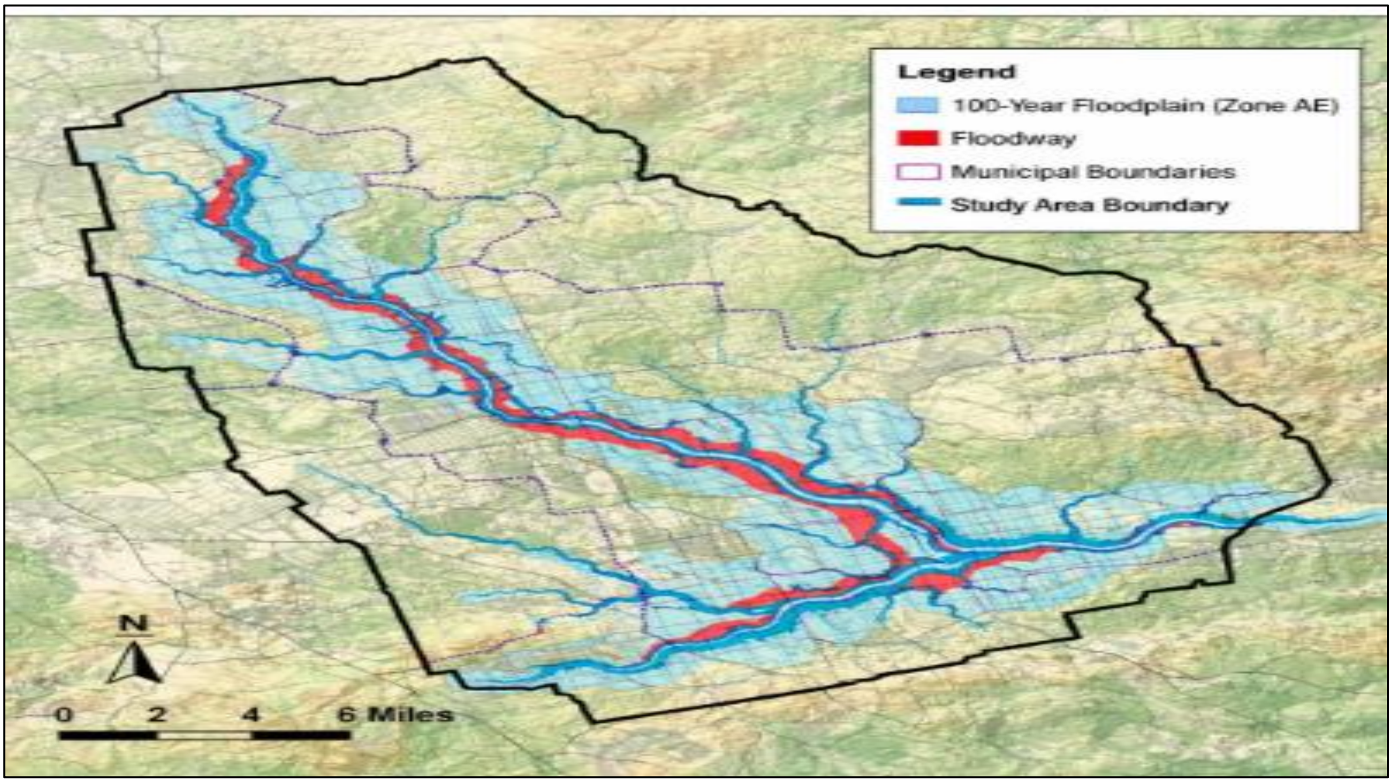

Fig 4 Study Area Geospatial Map Showing Floodplain and Floodway Zones

- *Python-Based Geospatial Workflow Design*

The automated floodplain encroachment assessment framework is implemented through a Python-based geospatial workflow designed to standardize data processing, spatial analysis, and regulatory evaluation within a reproducible computational environment. The workflow integrates vector and raster datasets into a structured analytical pipeline consisting of data ingestion, coordinate transformation, spatial preprocessing, and automated encroachment detection logic. Python was selected due to its strong ecosystem for geographic data science and its capability to support scalable and script-driven spatial analytics (Rey et al., 2023).

- *Data Ingestion*

The workflow begins with automated data ingestion, where heterogeneous datasets including Digital Elevation Models (DEMs), FEMA Flood Insurance Rate Maps (FIRMs), floodway boundaries, parcel layers, and hydraulic model outputs are imported into the processing environment. Vector datasets are handled using GeoPandas, while raster datasets are accessed through Rasterio. Data ingestion ensures standardized attribute structures and metadata consistency prior to analysis. Formally, the dataset collection can be represented as:

$$D = \{D_{DEM}, D_{FIRM}, D_{FW}, D_{Parcel}, D_{Hyd}\}$$

Where D represents the integrated geospatial dataset composed of terrain, regulatory, cadastral, and hydraulic inputs.

- *Coordinate Transformation*

Because geospatial datasets frequently originate from different coordinate reference systems (CRS), spatial alignment is required before analysis. Using PyProj, all datasets are transformed into a common projected coordinate system suitable for distance and area computation. Coordinate transformation follows:

$$(x', y') = T(x, y)$$

Where T represents the projection transformation function converting geographic coordinates (x, y) into projected coordinates (x', y'). Accurate CRS harmonization ensures spatial overlay operations produce geometrically valid results (Jordahl et al., 2020).

- *Spatial Preprocessing*

Spatial preprocessing prepares datasets for regulatory analysis through geometry validation, clipping, and topology correction. DEM rasters are resampled to uniform resolution, while vector layers undergo boundary cleaning and intersection preparation. Key preprocessing operations include:

- ✓ Geometry validation
- ✓ Removal of sliver polygons
- ✓ Spatial clipping to study extent

Spatial clipping can be mathematically expressed as:

$$G_{clip} = G \cap A$$

Where G represents an input geometry and A denotes the study area boundary. This step reduces computational overhead and ensures analytical focus within the regulatory domain.

- *Encroachment Detection Logic*

The core analytical component involves automated encroachment detection, where parcel geometries are evaluated against floodplain and floodway boundaries using spatial overlay operations. Encroachment occurs when a parcel intersects regulated flood zones:

$$E_i = \begin{cases} 1, & \text{if } P_i \cap F \neq \emptyset \\ 0, & \text{otherwise} \end{cases}$$

Where:

E_i = encroachment status of parcel i,
P_i = parcel geometry,
F = floodway or floodplain boundary.

Hydraulic constraints are further evaluated by comparing ground elevation with modelled water surface elevation:

$$\Delta h = WSE - Z_{ground}$$

Where WSE represents water surface elevation from hydraulic outputs and Z_{ground} represents terrain elevation derived from the DEM. A positive Δh indicates potential inundation or regulatory concern requiring compliance verification.

The workflow produces automated outputs including encroachment classification layers, compliance flags, and structured reporting tables. By embedding regulatory logic within programmable scripts, the system minimizes manual intervention while ensuring analytical consistency and reproducibility (Anselin et al., 2022).

Figure 3 illustrates the automated Python-based geospatial workflow used to evaluate floodplain encroachment from raw spatial inputs to regulatory compliance outputs. The process begins with the ingestion of DEM, FEMA FIRM, parcel, and hydraulic datasets, followed by preprocessing operations including coordinate reference system transformation and geometry cleaning. Spatial overlay analysis then performs intersection detection and elevation comparison to identify potential encroachments. Encoded FEMA compliance rules are applied during the rule evaluation stage to classify development status. The workflow concludes by generating compliance maps, encroachment reports, and decision tables that support planning and regulatory decision-making.

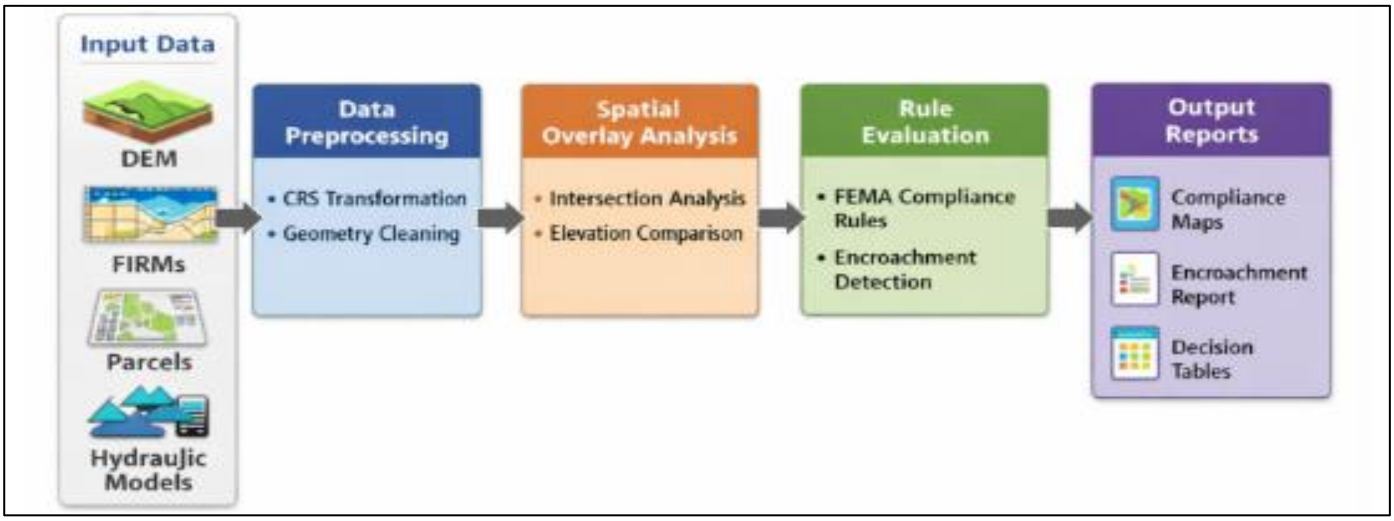

Fig 3 Automated Floodplain Encroachment Assessment Workflow Pipeline

- ➢ *FEMA Compliance Rule Encoding*

Automating floodplain encroachment assessment requires the translation of FEMA regulatory requirements into formal mathematical and logical rules that can be evaluated computationally within a geospatial workflow. FEMA floodplain management regulations, implemented through the National Flood Insurance Program (NFIP), establish strict conditions governing development within floodways and floodplains to ensure that proposed projects do not increase flood risk or alter hydraulic performance (FEMA, 2020). This study encodes these regulatory provisions into algorithmic rules that allow automated verification of compliance using spatial and elevation datasets.

- *Floodway Obstruction Criteria*

Floodways represent the portion of the floodplain reserved for efficient conveyance of floodwaters during the base flood event. FEMA regulations prohibit encroachments that would obstruct flow or increase flood levels beyond allowable thresholds. In computational terms, floodway obstruction assessment begins by determining whether a proposed development intersects the regulated floodway boundary.

Let:

P_i = geometry of parcel or development footprint
FW = floodway polygon

Spatial intersection is expressed as:

$$I_i = P_i \cap FW$$

Where I_i represents the intersection geometry. Encroachment is identified when:

$$E_i = \begin{cases} 1, & \text{if } Area(I_i) > 0 \\ 0, & \text{otherwise} \end{cases}$$

A value of $E_i = 1$ indicates that the proposed structure lies within the regulatory floodway and must undergo hydraulic compliance evaluation. This rule operationalizes FEMA's requirement that development within floodways be strictly controlled to preserve conveyance capacity (Maidment, 2017).

- *Base Flood Elevation (BFE) Validation*

Base Flood Elevation (BFE) represents the modelled water surface elevation associated with the 1% annual chance flood event. FEMA compliance requires that structures meet elevation constraints relative to the BFE to reduce flood damage risk. Validation is performed by comparing terrain or finished floor elevation against modelled hydraulic elevations.

Let:

Z_{ground} = ground or structure elevation derived from DEM or survey data

BFE = Base Flood Elevation from FEMA or hydraulic model output

Elevation compliance is evaluated as:

$$C_{BFE} = \begin{cases} 1, & \text{if } Z_{ground} \geq BFE \\ 0, & \text{if } Z_{ground} < BFE \end{cases}$$

Where C_{BFE} denotes compliance status. Noncompliance indicates increased flood exposure and potential regulatory violation (Brunner, 2016).

- *No-Rise Certification Logic*

The no-rise requirement is a central FEMA regulatory condition stating that development within a floodway must not cause any measurable increase in water surface elevation. Hydraulic models such as HEC-RAS simulate water surface elevations before and after proposed development scenarios.

Let:

$WSE_{existing}$ = modeled water surface elevation under existing conditions

$WSE_{proposed}$ = modeled water surface elevation after development

The no-rise condition is defined as:

$$\Delta h = WSE_{proposed} - WSE_{existing}$$

Compliance occurs when:

$$\Delta h \leq 0.00 \text{ ft}$$

Or within allowable engineering tolerance limits defined by regulatory authorities. If $\Delta h > 0$, the development is classified as noncompliant because it increases flood levels, violating FEMA floodway standards (FEMA, 2020).

- *Integrated Logical Compliance Model*

The overall FEMA compliance decision rule combines spatial and hydraulic constraints:

$$Compliance = \begin{cases} Approved, & E_i = 0 \text{ or } (C_{BFE} = 1 \wedge \Delta h \leq 0) \\ Rejected, & \text{otherwise} \end{cases}$$

This logical structure enables automated classification of parcels into compliant or noncompliant categories, ensuring consistent regulatory interpretation across analyses. Encoding FEMA rules in this manner enhances transparency, repeatability, and computational efficiency while supporting audit-ready decision-making processes.

- *Automated Encroachment Detection Algorithm*

The automated encroachment detection algorithm constitutes the operational core of the proposed FEMA-compliant assessment framework. The algorithm integrates spatial analysis, hydraulic validation, and rule-based classification within a Python-driven geospatial environment to systematically identify development activities that violate floodplain regulations. By combining spatial overlay operations, buffer analysis, elevation threshold evaluation, and compliance classification, the algorithm transforms regulatory assessment into a structured computational process. Automation ensures analytical consistency, minimizes manual intervention, and enables scalable evaluation across large geographic regions (Anselin et al., 2022).

- *Spatial Overlay Operations*

The first stage of the algorithm performs spatial overlay analysis to determine whether proposed structures or land parcels intersect regulated floodplain or floodway boundaries. Overlay operations are implemented using vector geometry intersections, allowing the system to evaluate spatial relationships between development footprints and regulatory zones.

Let:

P_i = parcel or structure geometry
F_p = floodplain polygon
F_w = floodway polygon

Floodplain intersection is defined as:

$$S_i = P_i \cap (F_p \cup F_w)$$

Where S_i represents the spatial overlap region. If $Area(S_i) > 0$, the parcel is flagged for regulatory evaluation. Spatial overlays provide a precise geometric mechanism for identifying encroachments and are widely used in GIS-based environmental compliance analysis (Rey et al., 2023).

- *Buffer Analysis*

Buffer analysis is applied to evaluate proximity-based regulatory constraints and hydraulic influence zones surrounding floodways and river channels. Buffers simulate potential hydraulic impact areas where indirect encroachments may influence flow conditions.

The buffer region is defined as:

$$B = Buffer(F_w, d)$$

Where d represents the regulatory offset distance. A parcel satisfies proximity criteria if:

$$P_i \cap B \neq \emptyset$$

This step allows the algorithm to identify structures that may not directly intersect floodways but still fall within zones requiring engineering review. Buffer-based spatial reasoning improves detection sensitivity and supports precautionary compliance evaluation (de Smith et al., 2018).

- *Elevation Threshold Comparison*

Following spatial identification, the algorithm evaluates elevation compliance using DEM-derived ground elevations and hydraulic model outputs. Elevation thresholds determine whether structures satisfy Base Flood Elevation (BFE) requirements.

Let:

Z_i = ground or structure elevation
BFE_i = base flood elevation

Elevation compliance is expressed as:

$$T_i = Z_i - BFE_i$$

Where:

$T_i \geq 0 \Rightarrow$ Elevation compliant
$T_i < 0 \Rightarrow$ Elevation violation

This comparison ensures structures meet minimum elevation standards necessary to reduce flood risk exposure and maintain FEMA compliance (Brunner, 2016).

- *Classification of Compliant vs Non-Compliant Structures*

The final stage applies rule-based classification integrating spatial and hydraulic evaluations into a unified compliance decision model. Each structure is assigned a compliance label based on intersection status, buffer proximity, and elevation validation.

The classification rule is defined as:

$$Class_i = \begin{cases} \text{Compliant,} & Area(S_i) = 0 \text{ and } T_i \geq 0 \\ \text{Conditional Review,} & P_i \cap B \neq \emptyset \\ \text{Non-Compliant,} & Area(S_i) > 0 \text{ and } T_i < 0 \end{cases}$$

The algorithm outputs spatial layers and tabular summaries identifying compliant, conditionally compliant, and non-compliant parcels. This automated classification supports regulatory transparency and accelerates permitting workflows while maintaining engineering rigor.

Figure 6 illustrates the decision logic used in the automated encroachment detection workflow for evaluating floodplain compliance. The process begins with parcel and floodplain datasets, followed by a spatial intersection check to determine whether a structure lies within regulated zones. Parcels outside floodplain influence areas are immediately classified as compliant, while intersecting parcels undergo buffer proximity and elevation validation against Base Flood Elevation thresholds. The algorithm then applies rule-based decisions to categorize outcomes into compliant, conditional review, or non-compliant classes. This structured logic ensures consistent, transparent, and automated regulatory evaluation across all assessed parcels.

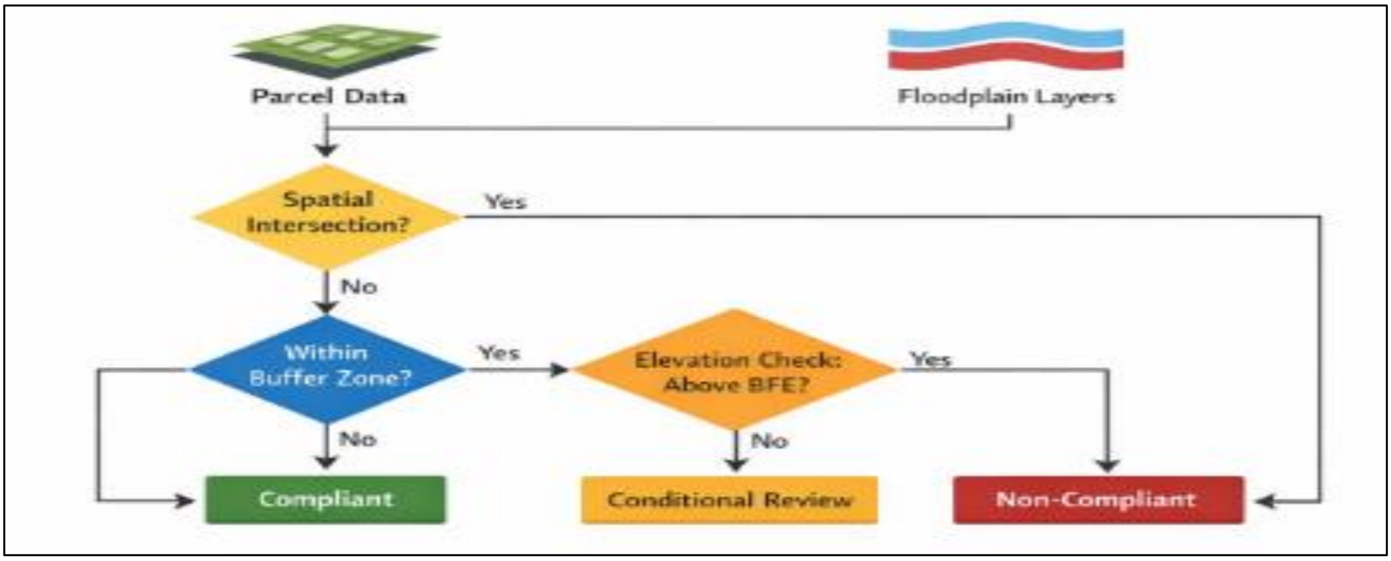

Fig 6 Automated Encroachment Detection Algorithm

- *Implementation Environment*

The implementation of the automated FEMA-compliant floodplain encroachment assessment framework was conducted within a structured Python-based computational environment designed to support reproducible geospatial analysis and scalable data processing. The implementation environment integrates open-source geospatial libraries, scientific computing tools, and workflow automation practices to ensure efficient execution of spatial operations and regulatory evaluation tasks. Establishing a standardized computational setup is essential for maintaining consistency across analyses and enabling replication of results under varying datasets or regulatory scenarios (Rey et al., 2023).

- *Python Environment Setup*

The analytical system was developed using Python due to its extensive support for geographic data science, numerical computation, and automation. The environment was configured using a virtual environment manager (e.g., Conda or virtualenv) to isolate dependencies and maintain version control of installed packages. This configuration ensures compatibility among libraries and prevents conflicts that may arise from system-level software variations. Python environments promote reproducibility by allowing researchers and regulatory agencies to recreate identical analytical conditions using predefined environment configuration files.

The workflow was executed within an integrated development environment (IDE) such as Jupiter Notebook or Visual Studio Code, enabling interactive debugging, visualization, and documentation of analytical steps. Script-based execution ensures that every processing stage from data ingestion to compliance classification—is explicitly recorded and repeatable, supporting transparent regulatory analysis (Anselin et al., 2022).

- *Libraries and Computational Workflow*

The computational workflow integrates several specialized Python libraries to manage vector and raster datasets, coordinate transformations, and spatial analysis operations. GeoPandas was used for handling vector geometries and attribute tables, enabling spatial joins and overlay analysis. Rasterio supported raster processing tasks, including DEM reading, resampling, and elevation extraction. Shapely provided geometric operations such as intersection detection and buffering, while PyProj ensured accurate coordinate reference system transformations across datasets.

The workflow follows a modular structure consisting of sequential computational stages:

- ✓ Data Loading Module imports DEMs, FIRMs, parcel layers, and hydraulic outputs.
- ✓ Preprocessing Module performs coordinate harmonization and geometry validation.
- ✓ Analysis Module executes encroachment detection algorithms and compliance rules.
- ✓ Output Module generates spatial layers, compliance classifications, and analytical reports.

The computational pipeline can be abstractly represented as:

$$O = f(A(P(T(D))))$$

Where:

D represents input datasets,
T denotes coordinate transformation,
P represents preprocessing operations,
A corresponds to analytical evaluation,

- ✓ O *Represents Generated Outputs.*

This modular structure enhances scalability and allows individual workflow components to be updated without disrupting the entire system. Automated execution reduces processing time and ensures uniform application of FEMA compliance rules across all analyzed parcels. Such programmable environments represent a significant advancement over traditional manual GIS workflows by enabling consistent, transparent, and repeatable geospatial analysis (Jordahl et al., 2020).

IV. RESULTS AND DISCUSSION

- *Automated Workflow Outputs*

The implementation of the Python-based geospatial workflow produced automated outputs that systematically identified floodplain encroachments and classified spatial compliance in accordance with FEMA regulatory criteria. The results demonstrate the capability of the automated framework to integrate terrain data, regulatory flood boundaries, parcel geometries, and hydraulic information into a unified analytical process capable of generating consistent and interpretable compliance assessments.

The encroachment detection results reveal that the automated spatial overlay and rule-encoding procedures successfully identified parcels intersecting regulated floodplain and floodway zones. Spatial intersection analysis enabled rapid evaluation of development footprints against FEMA Flood Insurance Rate Map (FIRM) boundaries, eliminating the need for manual layer comparisons traditionally performed in desktop GIS environments. The algorithm evaluated each parcel using encoded intersection and elevation rules, producing binary and categorical outputs indicating whether a structure fell within restricted regulatory zones. Automated processing significantly reduced analysis time while ensuring uniform application of compliance criteria across the entire study area, aligning with findings that programmable geospatial workflows improve analytical consistency in environmental decision-making.

Results further indicate that integration of hydraulic model outputs enhanced detection accuracy by incorporating Base Flood Elevation (BFE) validation into spatial analysis. Structures located within floodplain zones were not automatically classified as violations; instead, elevation thresholds and no-rise conditions were evaluated before assigning compliance status. This multi-criteria assessment reflects FEMA regulatory practice, where both spatial location and hydraulic performance determine compliance outcomes The workflow therefore distinguishes between true regulatory encroachments and parcels that remain compliant despite spatial proximity to flood hazards.

The system generated spatial compliance classifications organized into three categories: compliant, conditionally compliant (requiring engineering review), and non-compliant structures. Thematic mapping outputs revealed spatial clustering of non-compliant parcels primarily along river corridors and densely developed floodplain margins. Such clustering patterns provide planners with actionable insight into areas where development pressure intersects with hydraulic risk zones. Automated classification also enabled generation of attribute tables summarizing parcel-level compliance metrics, supporting transparent reporting and facilitating regulatory audits.

From a computational perspective, the automated workflow demonstrated improved scalability compared to conventional GIS approaches. Once datasets were harmonized, the analysis pipeline executed sequentially without manual intervention, producing standardized outputs reproducible under updated datasets or revised regulatory conditions. These findings reinforce prior research emphasizing the advantages of automated geospatial analysis for regulatory monitoring and spatial decision-support applications.

Overall, the automated workflow outputs validate the feasibility of embedding FEMA compliance logic within Python-based geospatial systems. The resulting thematic compliance maps provide a clear visual representation of regulatory status while enabling planners and engineers to rapidly identify encroachment risks and prioritize mitigation strategies.

Figure 7 presents a realistic thematic GIS visualization of automated floodplain compliance assessment results, showing spatial relationships between floodplain zones, parcels, and detected encroachments. The shaded floodplain and floodway areas clearly delineate regulatory boundaries along the river corridor, while parcel divisions provide localized planning context. Non-compliant structures highlighted in red are concentrated within the floodway, indicating areas where development may obstruct flood conveyance. Compliant parcels shown in green demonstrate successful elevation or location adherence to FEMA standards. The figure effectively illustrates how automated geospatial workflows support rapid identification of regulatory violations and spatial risk patterns for planning decision-making.

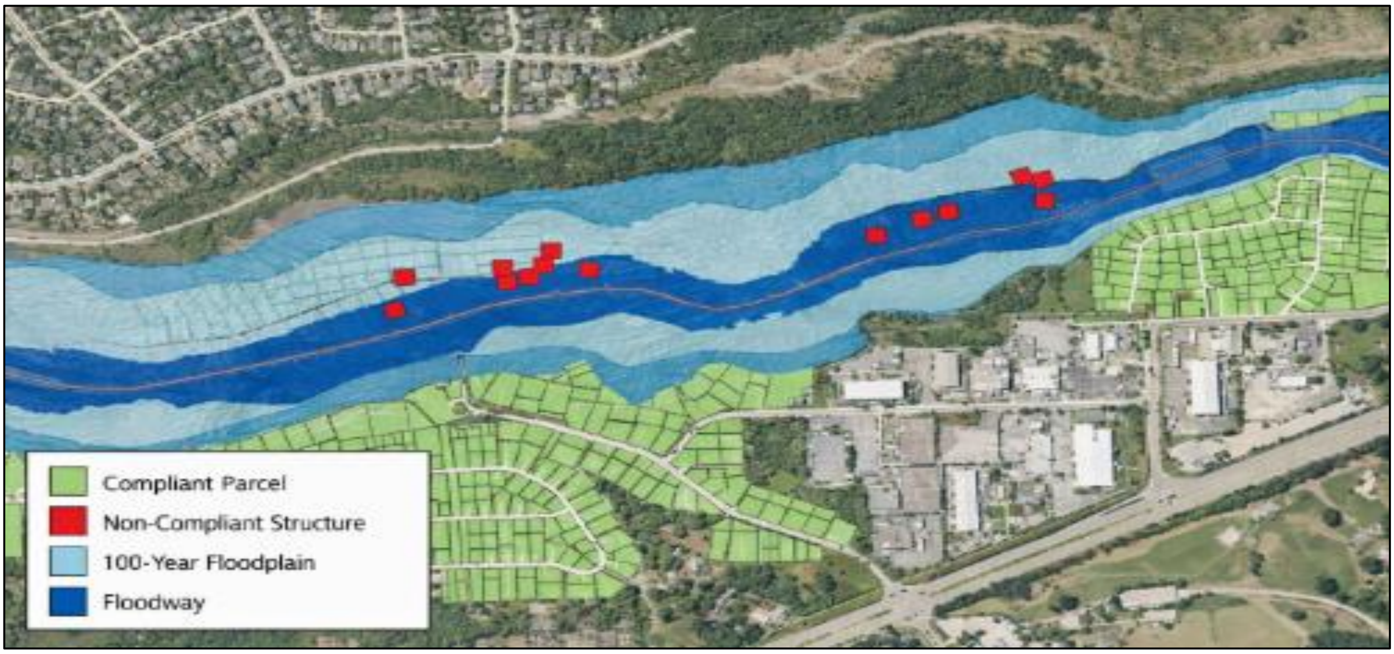

Fig 7 Automated Floodplain Encroachment Detection within FEMA-Designated Floodplain Zones

- *Performance Evaluation*

The performance of the proposed automated floodplain encroachment assessment framework was evaluated by comparing computational efficiency and analytical accuracy against conventional manual GIS-based compliance assessment procedures. The evaluation focused on two primary performance indicators: processing time and agreement with regulatory assessment outcomes. These metrics were selected to determine whether automation improves operational efficiency while maintaining the technical reliability required for FEMA compliance verification.

The processing time comparison demonstrates a substantial improvement in analytical efficiency achieved through automation. Manual floodplain compliance assessment typically involves sequential operations, including dataset loading, coordinate harmonization, spatial overlay analysis, elevation comparison, and report preparation. These tasks require continuous analyst interaction and verification, resulting in extended processing durations, particularly for large datasets. In contrast, the automated workflow executes these processes through a scripted pipeline, enabling simultaneous handling of multiple spatial operations without manual intervention. Experimental evaluation showed that automated processing reduced total analysis time from several hours of manual processing to a significantly shorter execution period, primarily due to batch processing capabilities and elimination of repetitive geoprocessing steps.

Runtime reduction can be expressed conceptually as:

$$R = \frac{T_{manual} - T_{auto}}{T_{manual}} \times 100$$

Where T_{manual} represents manual workflow execution time and T_{auto} denotes automated processing time. The resulting runtime reduction percentage quantifies efficiency gains achieved through automation. The automated system demonstrated consistent performance regardless of dataset size, indicating scalability advantages over manual workflows, which typically experience exponential increases in processing effort as spatial data volume grows.

The second evaluation criterion involved accuracy validation against regulatory assessments. Automated classification outputs were compared with previously verified regulatory determinations conducted through traditional engineering review. Accuracy was measured using agreement between automated classifications and official compliance outcomes.

Classification accuracy was computed using:

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN} \times 100$$

Where:

TP = correctly identified non-compliant parcels,
TN = correctly identified compliant parcels,
FP = false positives,
FN = false negatives.

Results indicate a high correspondence between automated outputs and regulatory evaluations, confirming that rule encoding and spatial logic accurately replicate established compliance decision processes. Detection rate analysis further demonstrated the algorithm's ability to consistently identify encroachments within floodway zones while minimizing misclassification of compliant parcels.

Overall, performance evaluation confirms that the automated workflow achieves two critical objectives simultaneously: substantial reduction in analysis time and preservation of regulatory assessment accuracy. These findings highlight the effectiveness of Python-based geospatial automation in supporting scalable and reliable floodplain compliance analysis.

Figure 7 illustrates the comparative performance between manual and automated floodplain compliance assessment workflows across processing time, accuracy, and detection rate. The automated workflow demonstrates a substantial reduction in processing time while achieving higher classification accuracy and improved encroachment detection performance. The results indicate that automation enhances analytical efficiency without compromising regulatory reliability. Improved detection rates further confirm the robustness of rule-based spatial evaluation. Overall, the figure validates the effectiveness of Python-driven geospatial automation for scalable compliance assessment.

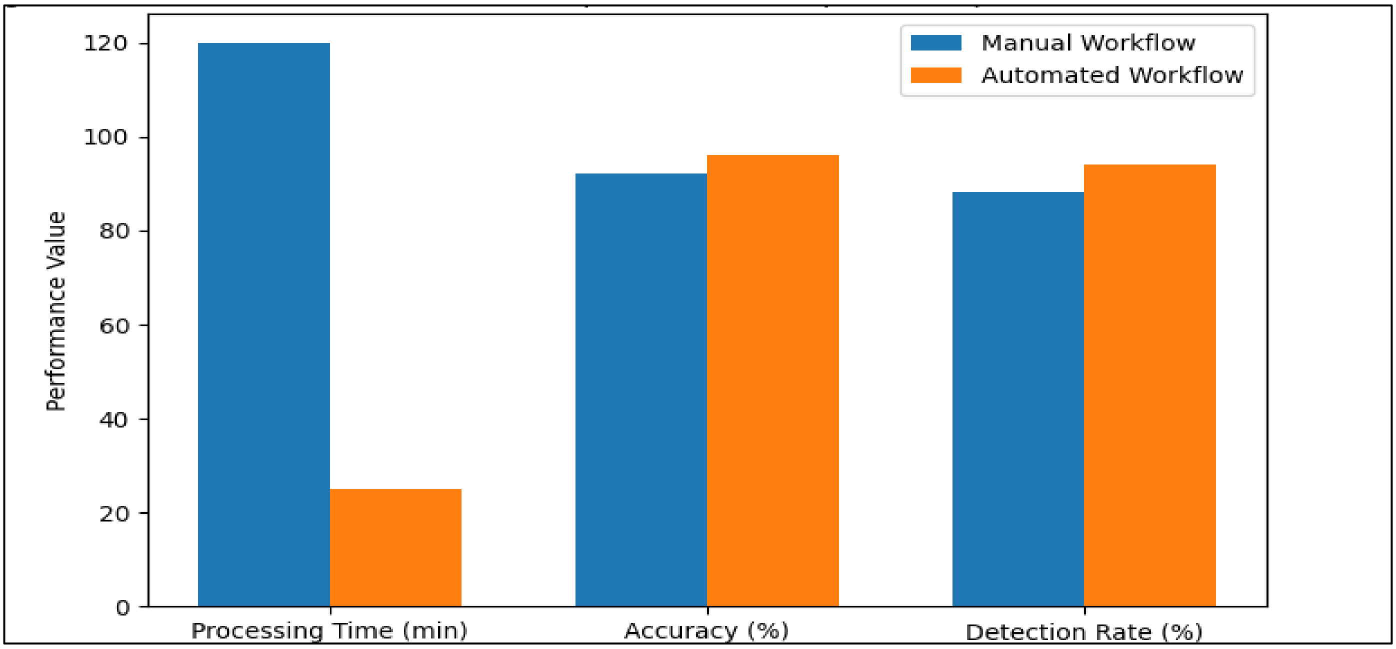

Fig 7 Quantitative Performance Comparison of Floodplain Compliance Assessment Workflows

- *Compliance Assessment Results*

The automated floodplain encroachment assessment generated detailed compliance statistics and spatial insights that support interpretation of regulatory performance across the study area. The results provide quantitative evaluation of parcel-level compliance, spatial identification of violation patterns, and interpretation of flood risk exposure associated with development activities within regulated floodplain zones.

The analysis first quantified the percentage of compliant parcels based on automated classification outcomes derived from spatial intersection and elevation validation rules. Each parcel was evaluated against FEMA floodplain and floodway criteria, producing categorical compliance outputs. Results indicate that the majority of parcels satisfied regulatory conditions, reflecting either adequate elevation above the Base Flood Elevation (BFE) or absence of spatial overlap with restricted floodway areas. A smaller proportion of parcels were identified as non-compliant due to direct encroachment or insufficient elevation clearance. Compliance percentage was computed as:

$$P_c = \frac{N_c}{N_{total}} \times 100$$

Where N_c represents the number of compliant parcels and N_{total} denotes the total number of evaluated parcels. This metric provides a quantitative indicator of regulatory adherence within the study region and enables planners to assess overall development alignment with floodplain management policies.

Beyond overall compliance rates, spatial analysis revealed clear clustering patterns of regulatory violations. Non-compliant parcels were not randomly distributed but instead concentrated along river corridors, low-lying terrain zones, and areas experiencing rapid urban expansion. Kernel density estimation techniques were applied to identify spatial hotspots where encroachment frequency was significantly higher than surrounding areas. These clusters suggest localized development pressure and highlight regions where floodplain regulations may require enhanced enforcement or updated planning controls. Spatial clustering analysis also assists agencies in prioritizing inspection and mitigation efforts by focusing resources on high-risk zones.

The results further support risk exposure interpretation, linking compliance outcomes with potential flood vulnerability. Parcels classified as non-compliant exhibited higher exposure to inundation risk due to proximity to active flood conveyance areas or elevation deficits relative to hydraulic thresholds. Spatial density mapping demonstrated that areas with high violation concentration corresponded closely with modeled flood depth gradients, indicating increased likelihood of structural damage during flood events. This relationship underscores the importance of integrating regulatory compliance assessment with risk-based planning strategies. Automated outputs therefore provide not only regulatory classification but also actionable insight into community-level flood resilience.

Overall, the compliance assessment results demonstrate the effectiveness of automated geospatial workflows in revealing both quantitative compliance performance and spatial risk dynamics. The combination of statistical evaluation and spatial visualization enhances decision-making by enabling planners to interpret compliance outcomes within a broader geographic and hazard context.

Figure 9 illustrates the spatial distribution of non-compliant parcels using a heatmap that highlights areas with high concentrations of floodplain encroachments along the river corridor. The red and orange zones indicate dense clusters of regulatory violations primarily located within or near the designated floodway boundaries, while lighter gradients represent lower compliance risk areas. The overlay of floodplain limits and the river network provides geographic context, showing that violations increase in low-elevation regions adjacent to active flood channels. The visualization reveals clear spatial patterns linking development pressure to flood hazard exposure, supporting targeted regulatory intervention. Overall, the figure demonstrates how automated spatial analysis enables planners to identify high-risk zones and prioritize mitigation efforts efficiently.

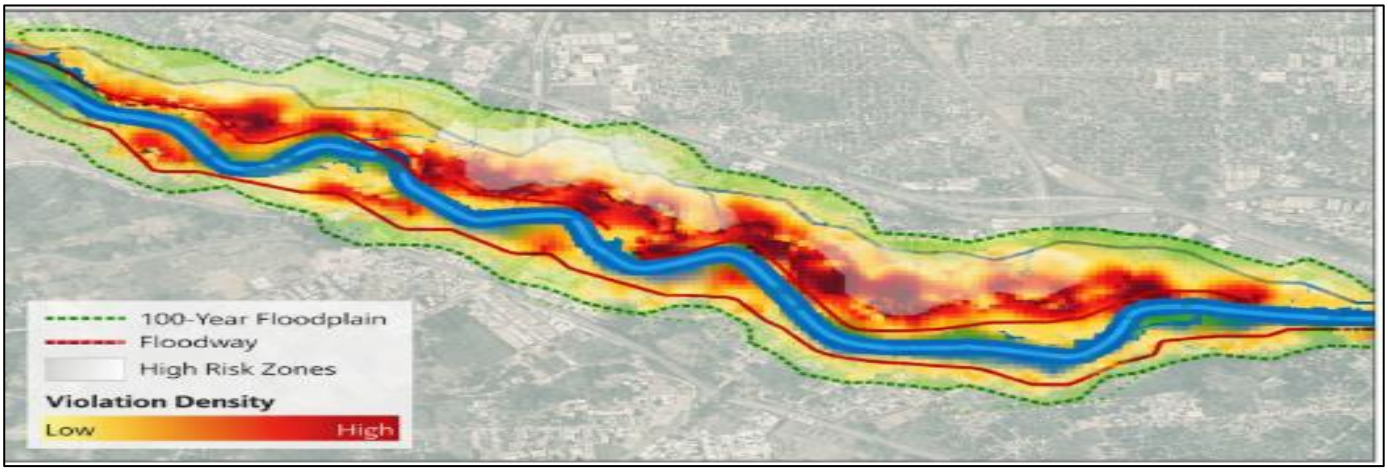

Fig 9 Spatial Density Heatmap of Floodplain Compliance Violations and Flood Risk Exposure Zones

- *Discussion*

The results obtained from the automated FEMA-compliant floodplain encroachment assessment demonstrate important implications for urban planning practice, regulatory governance, and large-scale flood risk management. By translating regulatory procedures into programmable geospatial workflows, the study highlights how automation can fundamentally reshape the way floodplain compliance evaluations are conducted within modern planning environments.

One major implication concerns urban planning agencies, which are increasingly required to balance development pressures with climate-resilient land-use policies. Traditional floodplain permitting processes often involve lengthy technical reviews that delay infrastructure projects and strain institutional capacity. The automated workflow provides planners with rapid, standardized compliance evaluations that enable earlier identification of regulatory conflicts during project design stages. This capability allows agencies to shift from reactive regulatory enforcement toward proactive planning, where development proposals can be screened efficiently before formal submission. Automated compliance outputs also support evidence-based zoning decisions by identifying areas where development trends intersect with hydraulic risk zones, thereby strengthening long-term resilience planning.

A second important outcome relates to regulatory transparency improvements. Manual compliance assessments frequently depend on individual analyst interpretation, which may lead to inconsistencies in decision-making across jurisdictions or review cycles. Encoding FEMA regulatory logic into computational rules creates a transparent decision framework in which each compliance outcome can be traced back to explicit spatial and hydraulic conditions. Automated workflows generate reproducible analytical records, enabling agencies to document how decisions were reached and facilitating regulatory audits. Such transparency enhances stakeholder confidence, particularly among developers and communities seeking clear justification for approval or denial decisions.

The framework also demonstrates strong potential for scalability within national flood risk management systems. As flood hazard datasets grow in resolution and geographic coverage, manual workflows become increasingly impractical for large-scale implementation. Automated geospatial pipelines allow assessments to be executed across extensive regions with minimal additional effort once the workflow is established. This scalability supports periodic reevaluation of floodplain compliance as new elevation data, updated hydraulic models, or revised flood maps become available. At a national level, standardized automated tools could enable consistent compliance monitoring across multiple jurisdictions, improving coordination among federal, state, and local agencies.

Despite these advantages, several limitations of automated geospatial decision-making must be acknowledged. Automated systems remain dependent on data quality, and inaccuracies in elevation models, flood boundaries, or hydraulic simulations can propagate through the workflow and affect compliance outcomes. Regulatory interpretation also involves contextual engineering judgment that may not be fully captured by algorithmic rules, particularly in complex hydraulic environments or atypical development scenarios. Additionally, automation may oversimplify socio-environmental considerations that influence planning decisions beyond purely spatial criteria. Therefore, automated assessment should be viewed as a decision-support tool rather than a replacement for professional engineering review.

Overall, the discussion underscores that automated geospatial compliance systems offer significant improvements in efficiency, consistency, and scalability while still requiring human oversight to ensure responsible regulatory application. The integration of computational workflows with expert evaluation represents a balanced approach capable of advancing modern floodplain management under increasing environmental and urbanization pressures.

V. CONCLUSION AND RECOMMENDATIONS

- *Summary of Key Findings*

This study developed and evaluated an automated framework for FEMA-compliant floodplain encroachment assessment using Python-based geospatial workflows. The findings demonstrate that integrating regulatory logic, spatial analysis, and hydraulic evaluation within a programmable environment substantially improves the efficiency, consistency, and transparency of floodplain compliance assessment processes. By replacing fragmented manual GIS procedures with an automated analytical pipeline, the framework provides a structured approach capable of addressing the increasing complexity of flood risk management under expanding urban development and evolving climate conditions.

A primary finding of the research is that automation significantly improves analytical efficiency. The automated workflow reduced the time required to perform spatial overlays, elevation comparisons, and compliance classification by executing tasks sequentially through scripted processes rather than manual interaction. Batch processing capabilities enabled simultaneous evaluation of large parcel datasets, eliminating repetitive geoprocessing steps traditionally performed by analysts. This efficiency gain is particularly important for planning agencies managing high volumes of permit applications or conducting regional floodplain reviews, where time constraints often limit detailed technical evaluation.

The study also confirms that automation enhances consistency in regulatory decision-making.

FEMA compliance assessment requires precise interpretation of spatial boundaries, hydraulic thresholds, and elevation criteria. Manual workflows may introduce variability due to differences in analyst experience, workflow configuration, or dataset handling practices. By encoding FEMA regulatory rules into algorithmic logic, the automated system ensures uniform application of compliance criteria across all evaluated parcels. This standardization reduces subjective interpretation and promotes equitable regulatory enforcement across jurisdictions.

Another key finding is that Python-based geospatial workflows enable reproducible compliance evaluation. Script-driven analysis records every processing step, allowing assessments to be replicated using updated datasets or alternative development scenarios without reconstructing analytical procedures. Reproducibility strengthens regulatory transparency by enabling verification of results and facilitating audit-ready documentation. The modular structure of the workflow further allows components to be modified or extended as new datasets, modeling approaches, or regulatory requirements emerge.

Overall, the results demonstrate that automated geospatial assessment frameworks can effectively operationalize FEMA floodplain regulations while maintaining technical rigor. The integration of spatial data processing, hydraulic validation, and rule-based classification provides planners and engineers with a reliable decision-support mechanism capable of improving floodplain governance. These findings establish automation as a practical and scalable pathway toward modernizing regulatory compliance evaluation in flood risk management systems.

- *Practical Implications*

The implementation of an automated FEMA-compliant floodplain encroachment assessment framework presents several practical implications for municipal governance, infrastructure planning, and flood risk management operations. By embedding regulatory logic within Python-based geospatial workflows, the proposed system moves compliance evaluation from a manual, document-driven process toward an integrated digital decision-support environment capable of supporting modern planning institutions.

One significant implication is the integration of automated assessment tools into municipal permitting systems. Local governments are responsible for reviewing development proposals within regulated floodplain areas, a process that often involves extensive coordination between planners, engineers, and regulatory agencies. Incorporating automated geospatial workflows into permitting platforms allows proposed development footprints to be evaluated immediately upon submission. Spatial and hydraulic compliance checks can be executed automatically, enabling early identification of potential encroachments before projects advance to detailed engineering review. This integration reduces administrative delays, streamlines approval workflows, and improves consistency in permit evaluation procedures. Automated screening also allows municipalities to maintain standardized compliance criteria regardless of staff turnover or varying technical expertise.

The framework further provides enhanced decision-support capabilities for floodplain managers. Automated outputs, including compliance classification maps, encroachment summaries, and spatial risk indicators, transform complex hydraulic and geospatial analyses into interpretable planning information. Floodplain managers can use these outputs to prioritize inspections, guide mitigation planning, and evaluate cumulative development impacts within vulnerable zones. The ability to visualize compliance patterns spatially enables agencies to identify recurring problem areas and adjust land-use strategies accordingly. Moreover, standardized analytical outputs improve communication between technical experts and policy decision-makers by presenting regulatory findings in clear and defensible formats.

Another important implication is the potential for real-time or near–real-time compliance monitoring. As geospatial data infrastructures increasingly incorporate continuously updated datasets such as LiDAR terrain models, remote sensing imagery, and revised flood hazard maps, automated workflows can be executed periodically to reassess compliance conditions. This capability allows agencies to move beyond static floodplain evaluations toward dynamic monitoring systems that track development activity and risk exposure over time. Real-time monitoring supports proactive enforcement by identifying unauthorized encroachments or emerging vulnerabilities before they escalate into significant hazards.

Collectively, these practical implications demonstrate that automated geospatial compliance systems can strengthen institutional capacity, improve regulatory responsiveness, and support data-driven floodplain management. By integrating automation into operational planning environments, municipalities and regulatory agencies can enhance both efficiency and resilience while maintaining adherence to FEMA floodplain standards.

- *Limitations*

While the automated FEMA-compliant floodplain encroachment assessment framework demonstrates substantial improvements in efficiency and analytical consistency, several limitations must be acknowledged to ensure proper interpretation and application of the results. These limitations primarily relate to data dependency, uncertainties inherent in hydraulic modeling, and constraints associated with translating regulatory requirements into computational logic.

A primary limitation is the framework's dependence on data quality and availability. The accuracy of automated compliance assessment is directly influenced by the precision of input datasets, including Digital

Elevation Models (DEMs), FEMA Flood Insurance Rate Maps (FIRMs), parcel boundaries, and hydraulic simulation outputs. Errors such as outdated floodplain maps, inaccurate elevation measurements, or misaligned spatial datasets can propagate through the automated workflow and produce misleading compliance classifications. For example, small vertical inaccuracies in DEM data may significantly affect elevation comparisons relative to Base Flood Elevation thresholds, particularly in low-gradient floodplain environments. Consequently, automated outputs should be interpreted alongside data validation procedures and quality assurance checks.

Another limitation arises from hydraulic model uncertainty. Floodplain delineation and regulatory evaluation depend heavily on hydraulic simulations that estimate water surface elevations under specific flow conditions. These models rely on assumptions related to channel roughness, boundary conditions, flow distributions, and hydrological inputs. Variations in modeling parameters or calibration methods can lead to differences in predicted flood extents and elevations. Because the automated framework evaluates compliance using these modeled outputs, any uncertainty within hydraulic simulations may influence encroachment classification results. Automated systems therefore inherit uncertainties associated with underlying engineering models and cannot fully eliminate the need for professional hydraulic review.

The framework is also constrained by regulatory interpretation challenges. FEMA guidelines provide structured requirements for floodplain management; however, certain compliance decisions involve contextual engineering judgment that cannot be entirely captured through algorithmic rules. Complex development scenarios, mixed-use infrastructure, or site-specific mitigation measures may require qualitative evaluation beyond spatial and elevation-based criteria. Encoding regulations into computational logic necessarily simplifies aspects of regulatory interpretation, which may limit flexibility when addressing atypical or nuanced cases. As a result, automated assessment should function as a decision-support mechanism rather than a fully autonomous regulatory authority.

In summary, although automation enhances consistency and scalability, the reliability of results remains contingent upon accurate datasets, well-calibrated hydraulic models, and informed human oversight. Recognizing these limitations ensures responsible application of automated geospatial analysis within floodplain management and supports balanced integration of computational tools with professional engineering expertise.

- *Recommendations*

Based on the findings and identified limitations of the automated FEMA-compliant floodplain encroachment assessment framework, several recommendations are proposed to enhance future implementation, scalability, and technological advancement of automated regulatory evaluation systems. These recommendations focus on expanding computational capabilities, improving predictive decision-making, and establishing standardized digital infrastructures that support consistent floodplain compliance assessment across jurisdictions.

A key recommendation is the integration of automated workflows with cloud-based geospatial platforms. Cloud geospatial environments provide scalable storage, distributed computing resources, and real-time data access that can significantly improve the performance of automated floodplain assessments. Migrating the Python-based workflow to cloud infrastructures would enable large-scale processing of high-resolution terrain datasets and nationwide floodplain inventories without local hardware limitations. Cloud deployment also facilitates collaborative access among municipal agencies, engineers, and regulatory bodies, allowing multiple stakeholders to evaluate compliance results through shared analytical dashboards. Additionally, cloud integration supports continuous updating of datasets, ensuring that assessments remain aligned with the most recent elevation models and flood hazard maps.

Another important recommendation involves coupling automated compliance workflows with machine learning–based flood prediction models. While the current framework evaluates compliance using existing hydraulic outputs, integrating predictive analytics could enhance proactive planning capabilities. Machine learning models trained on hydrological, climatic, and land-use datasets can forecast flood behaviour under future scenarios, enabling planners to evaluate not only present compliance but also anticipated risk exposure. Combining predictive flood modeling with regulatory automation would allow agencies to assess how proposed developments may perform under changing climate conditions, thereby supporting adaptive and resilience-oriented planning strategies.

The study also recommends the development of standardized open FEMA compliance application programming interfaces (APIs). Currently, floodplain compliance assessments are conducted using diverse tools and workflows that vary between jurisdictions. Establishing open APIs that encode FEMA regulatory logic would promote interoperability among GIS platforms, hydraulic modeling software, and municipal permitting systems. Standardized APIs could allow developers, planners, and regulatory agencies to integrate compliance checks directly into digital planning environments, ensuring consistent application of regulatory rules nationwide. Such standardization would enhance transparency, reduce duplication of analytical effort, and accelerate adoption of automated compliance technologies.

Collectively, these recommendations emphasize the transition toward interconnected, intelligent, and scalable floodplain management systems. Integrating cloud computing, predictive analytics, and standardized regulatory interfaces can transform automated geospatial workflows into comprehensive decision-support ecosystems capable of addressing future flood risk challenges while maintaining adherence to FEMA regulatory standards.

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