

Spatial and Temporal Analysis of Borrow-Pit Distribution in the Kano River and Hadejia Valley Irrigation Schemes, Nigeria

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ABSTRACT

Borrow pits supply earth materials for irrigation, construction and rehabilitation, but their spatial expansion can create persistent land-management concerns when excavation is poorly planned or when restoration is inadequate. This study analysed the spatial and temporal distribution of mapped borrow pits in the Kano River Irrigation Scheme (KRIS) and Hadejia Valley Irrigation Scheme (HVIS) in northern Nigeria for 1999, 2009, and 2019. Historical Google Earth imagery was visually interpreted and digitised, while 2019 locations were field-verified with a Garmin eTrex 32x receiver. Borrow-pit polygons and centroids were processed in ArcMap 10.3.1, and Average Nearest Neighbour analysis was used to assess spatial pattern. The mapped inventory increased from 19 to 21 and from 34 to 55 pits in KRIS, and from 21 to 26 and from 55 to 75 pits in HVIS across the three reference years. From 1999 to 2019, mapped pit counts increased by 78.9% in KRIS and 161.9% in HVIS, while the combined inventory rose from 40 to 89 pits. All six scheme-year distributions were clustered, with nearest-neighbour ratios of 0.50–0.51 in KRIS and 0.60–0.71 in HVIS. By 2019, mapped excavation footprints occupied approximately 180.2 ha in KRIS and 219.6 ha in HVIS. These results demonstrate the expansion and spatial concentration of mapped excavations, but do not, by themselves, establish the causes, legal status, or magnitude of environmental damage. The study provides a geospatial baseline for inventory management, field inspection, rehabilitation planning and future cumulative-impact assessment.

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INTRODUCTION

Borrow pits are excavated areas from which soil, laterite, clay, sand or gravel is removed for construction and earthworks. Their development is often associated with road, canal, and embankment works, but poorly restored or abandoned excavations can remain persistent landscape disturbances, contributing to soil loss, altered runoff, erosion, water accumulation, and public safety risks (Adedeji *et al.*, 2014; Nwachukwu *et al.*, 2017). These concerns are particularly relevant in irrigation landscapes, where excavation may compete directly with cultivated land and interact with canals, drains, access roads and groundwater. Demand for construction materials and fill can create incentives to source materials close to active work fronts because shorter haul distances reduce transport costs. In irrigation schemes, however, the same proximity that reduces construction costs can concentrate excavation around canals, roads and rehabilitation corridors. Without clear siting criteria, approval procedures, and enforceable restoration requirements, the environmental costs of material sourcing may be borne by farmers, irrigation authorities, and surrounding ecosystems. The Kano River Irrigation Scheme (KRIS) and Hadejia Valley Irrigation Scheme (HVIS) are major irrigated agricultural systems in northern Nigeria. Both have experienced successive construction, maintenance and rehabilitation activities. Project documentation associated with the Transforming Irrigation Management in Nigeria

(TRIMING) programme identifies rehabilitation of the equipped irrigation areas of KRIS and HVIS as major project activities. The two schemes therefore provide useful settings for examining the spatial concentration and temporal expansion of borrow pits.

Existing Nigerian studies have documented environmental impacts associated with inland sand extraction and abandoned borrow pits (Adedeji *et al.*, 2014; Nwachukwu *et al.*, 2017), while broader literature has highlighted the environmental governance challenges associated with aggregate extraction (Torres *et al.*, 2017; United Nations Environment Programme (UNEP), 2019). However, scheme-scale evidence showing how borrow-pit inventories and spatial patterns change through time remains limited. Counts alone cannot reveal whether excavations are evenly distributed or concentrated in particular parts of a scheme. Spatial statistics such as Average Nearest Neighbour analysis provide a transparent way to compare observed spacing with the spacing expected under complete spatial randomness (Esri, 2023).

Previous studies have applied remote sensing to map salinity in the Kano River Irrigation Programme (Mohammed *et al.*, 2018) and to assess the environmental impacts of borrow pits along the Kano-Ringim-Hadejia road (Bashir *et al.*, 2026). Additionally, studies have focused on the reclamation of borrow pits in Batagrawa, Katsina state (Gidado, *et al.*, 2023). There is a dearth of studies that have focused on multi-temporal GIS-based inventories to assess the evolution and clustering patterns of borrow pits and their proximity to

critical irrigation infrastructure. This study, therefore, intends to fill this gap by determining the spatial and temporal distribution of borrow pits in the Kano River and Hadejia Valley Irrigation Schemes between 1999 and 2019.

MATERIALS AND METHODS

Study Area

KRIS is located approximately 30 km south-west of Kano city in Kano State. The scheme is organised into eastern and western commands separated by the Shimar and Kano river systems. The source manuscript describes a designed area of about 22,000 ha and an active irrigable command area of approximately 14,262.2 ha used for the present analysis. The

command contains 49 sectors of varying sizes supplied by main, branch, distributary, and field canals.

HVIS is located about 150 km east of Kano city, principally in Auyo Local Government Area of Jigawa State, between the Hadejia and Kafin Hausa rivers. The original Phase I plan covered approximately 12,500 ha, although the developed and operational area has varied through time. The scheme occupies fertile fadama land where small-scale irrigation predated formal scheme development. The source manuscript notes contrasts between the generally sandier and lateritic materials in KRIS and the more clay-rich materials of HVIS, which may influence the suitability and demand for locally excavated fill.

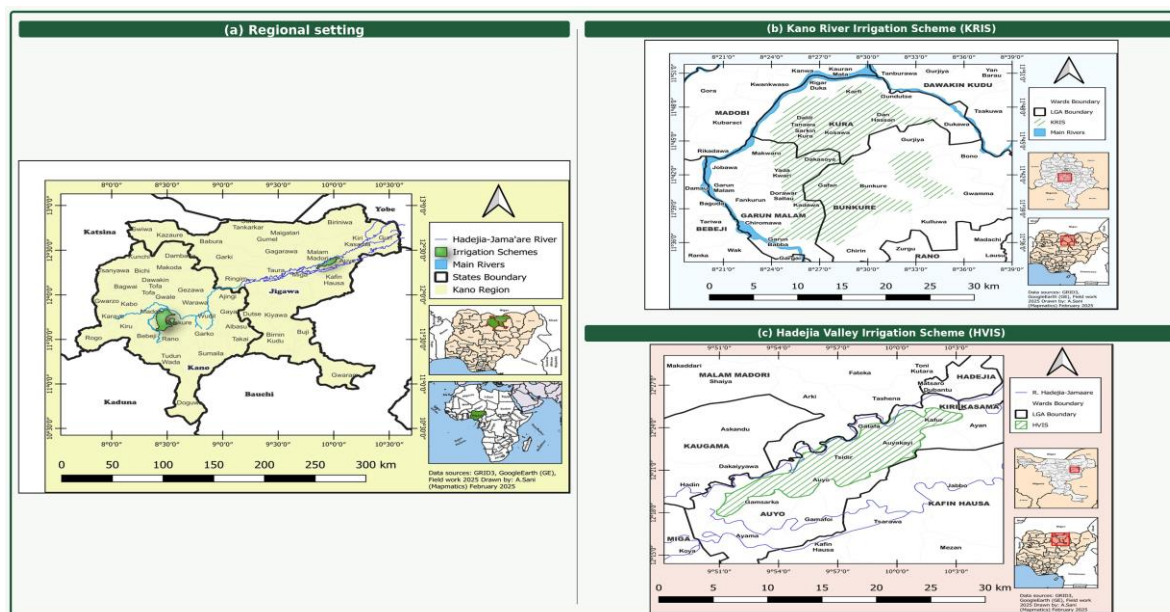


Figure 1: Location of the Kano River Irrigation Scheme (KRIS) and Hadejia Valley Irrigation Scheme (HVIS). Source: adapted from the study datasets and TRIMING (2017)

Research Design and Data Sources

A retrospective geospatial design was used to reconstruct the distribution of borrow pits at approximately decadal reference intervals (1999, 2009, and 2019). Historical imagery was examined directly in Google Earth Pro using the Historical Imagery time slider. The analytical year assigned to each inventory corresponds to the selected reference-year scene used for interpretation. Google Earth is a mosaic service, and scene-specific native ground-sampling distance is not consistently exposed in the exported imagery; therefore, a single nominal spatial resolution cannot be reported. The imagery dates displayed in Google Earth Pro should be recorded from the status bar/time slider in the archived project files for final reproducibility. Where an exact day was not available from the retained project record, the reference year rather than an invented acquisition date is reported. First, field coordinates of borrow pits observed in 2019 were recorded in decimal degrees using a Garmin eTrex 32x handheld Global Positioning System receiver. These points were used as field-verification aids for the 2019 inventory and to help locate corresponding landscape positions on historical imagery; they were not treated as an independent accuracy sample for the 1999 or 2009 classifications. Consequently, no retrospective classification-accuracy statistic is claimed for the historical inventories.

Borrow-pit boundaries were digitised manually as polygons only where an excavation could be distinguished from

surrounding land by a combination of visible indicators, including excavated morphology, exposed soil, sharp tonal or textural contrast, edge or shadow expression, water accumulation and discontinuity with cultivated land. Features whose boundaries were obscured by vegetation, standing water, shadow or poor image quality were mapped only when the excavation margin could be interpreted with reasonable confidence from adjacent visible edges or supporting dates; otherwise, they were excluded from the inventory. The mapped counts should therefore be interpreted as conservative inventories, particularly for older imagery. KML features were imported into ArcMap 10.3.1. Field coordinates were referenced to WGS 84, and spatial layers were projected to WGS 1984 UTM Zone 32N for planar distance and area calculations. Because handheld GPS observations and Google Earth imagery have different and variable positional uncertainties, the field points were used for feature verification rather than survey-grade boundary control; no sub-metre positional accuracy is claimed. Digital elevation data available through the Alaska Satellite Facility and NASA Earthdata repositories were used only as supporting terrain information and not to delineate pit boundaries.

Comparable fine-resolution imagery was not consistently available for the 1980s and early 1990s; the formal change analysis therefore begins in 1999. This reduces the risk of treating non-detection in coarser or poorer-quality imagery as

evidence of physical absence (Farr et al., 2007; Rabus et al., 2003). Differences in imagery clarity, season, viewing geometry and surface condition among reference years remain a source of detection uncertainty and are considered when interpreting temporal change.

Spatial Analysis

For each scheme and reference year, the centroids of mapped borrow-pit polygons were used as event locations for Average Nearest Neighbour (ANN) analysis. The analysis boundary was held constant through time within each scheme and corresponded to the scheme command area used in this study: approximately 14,262.2 ha for KRIS and 12,500 ha for HVIS. Using fixed scheme boundaries improves temporal comparability because the expected nearest-neighbour distance depends on the area over which events are evaluated. Euclidean distance was calculated in the projected WGS 1984 UTM Zone 32N coordinate system. The ANN statistic compares the observed mean nearest-neighbour distance with the mean distance expected under complete spatial randomness within the analysis area. The nearest-neighbour ratio (R) is expressed as:

$$R = \bar{D}_o / \bar{D}_e$$

Where $\bar{D}_o$ is the observed mean nearest-neighbour distance, and $\bar{D}_e$ is the expected mean nearest-neighbour distance under a random distribution within the analysis area. Values below 1 indicate clustering, values near 1 indicate a pattern consistent with randomness, and values above 1 indicate dispersion. The associated z-score was used to evaluate the departure from the null hypothesis of complete spatial

randomness; negative z-scores indicate clustering, with more negative values providing stronger evidence against the null under the test assumptions (Esri, 2023).

Counts, percentage change, mapped excavation footprint, and nearest-neighbour outputs were summarised for comparison. Temporal differences are described as changes in the mapped inventory rather than direct measures of excavation rates because detectability varied with imagery quality and surface conditions. The analysis focuses on spatial association and does not, by itself, establish the legal status or operator of individual pits, the precise cause of each excavation, or the magnitude of environmental harm. Interpretations relating to rehabilitation works, informal extraction, and transport-cost incentives are therefore treated as plausible explanations, supported by field observations and the project context, rather than as causal estimates.

RESULTS AND DISCUSSION

Temporal Change in Borrow-pit Inventory

The mapped borrow-pit inventory increased in both schemes, with a larger numerical increase in HVIS. KRIS increased from 19 mapped pits in 1999 to 21 in 2009 and 34 in 2019. HVIS increased from 21 mapped pits in 1999 to 26 in 2009 and 55 in 2019. Over the full study period, the mapped inventory therefore increased by 78.9% in KRIS and 161.9% in HVIS, while the combined mapped inventory increased from 40 to 89 pits (122.5%). These figures represent features detectable and interpretable in the imagery available for each reference year; differences in image quality mean that they should not be interpreted as exact excavation rates.

Table 1: Temporal Change in Mapped Borrow-Pit Numbers

Scheme	1999	2009	2019	Change 1999–2019	Percentage change
KRIS	19	21	34	+15	78.9%
HVIS	21	26	55	+34	161.9%
Combined	40	47	89	+49	122.5%

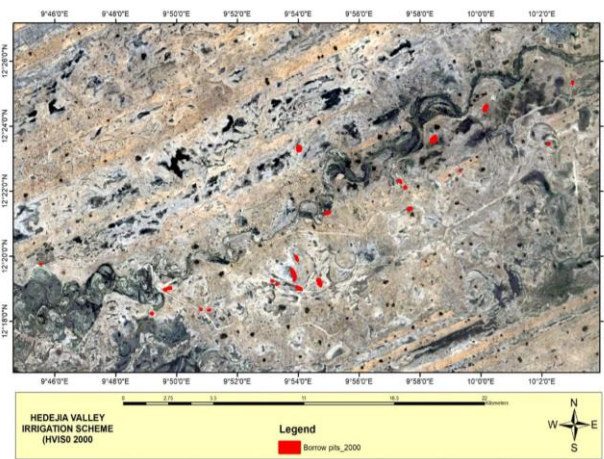
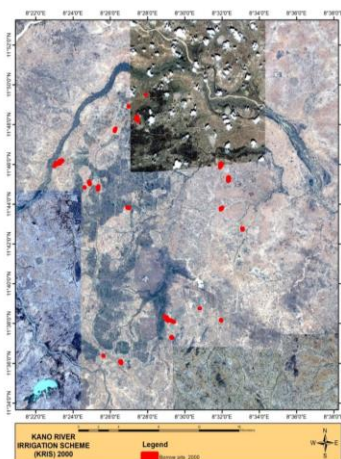


Figure 2: Borrow-pit distribution for the 1999 analytical reference-year inventory: (a) KRIS and (b) HVIS. Source: authors' geospatial analysis. The analytical year used throughout the text, tables and statistical analysis is 1999

In the 1999 mapped inventory, both schemes already contained concentrated excavation zones. The spatial association with accessible parts of the command areas is consistent with, but does not prove, an influence of access, material suitability or construction activity. Because the

inventory is based on features discernible in historical imagery, it should be interpreted as a conservatively mapped minimum, where small, vegetated, water-covered, or shallow pits were difficult to distinguish from surrounding land cover.

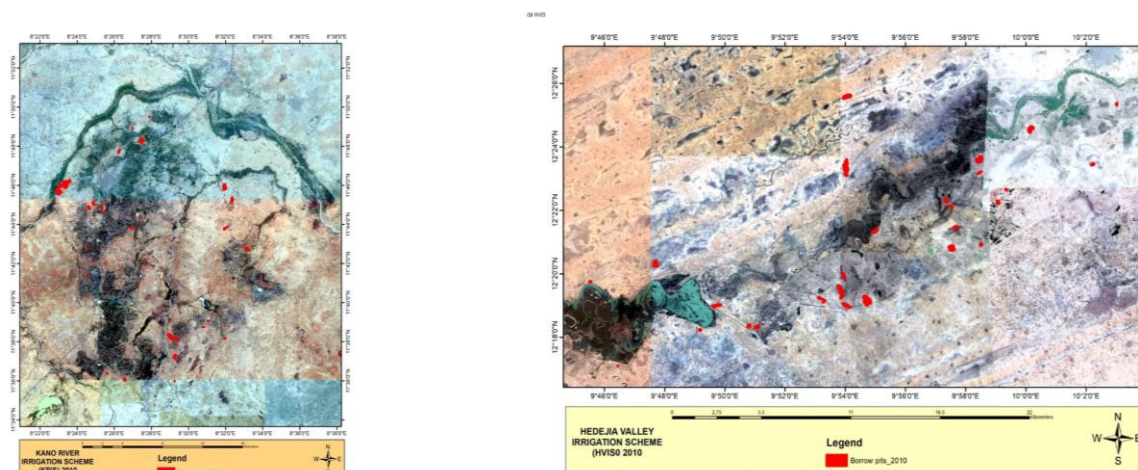


Figure 3: Borrow-pit distribution for the 2009 analytical reference-year inventory: (a) KRIS and (b) HVIS. Source: authors' geospatial analysis. The analytical year used throughout the text, tables and statistical analysis is 2009

By the 2009 analytical reference year, the mapped increase in pit numbers was modest in both schemes, while mapped disturbances remained concentrated in established excavation zones. Persistence of a mapped feature across image dates indicates continued landscape expression, but does not, by

itself, establish whether the pit remained active, was enlarged continuously, or had undergone partial restoration. Repeated occurrences near canals, roads, and previously disturbed locations are therefore interpreted as a spatial association rather than proof of a specific excavation cause.

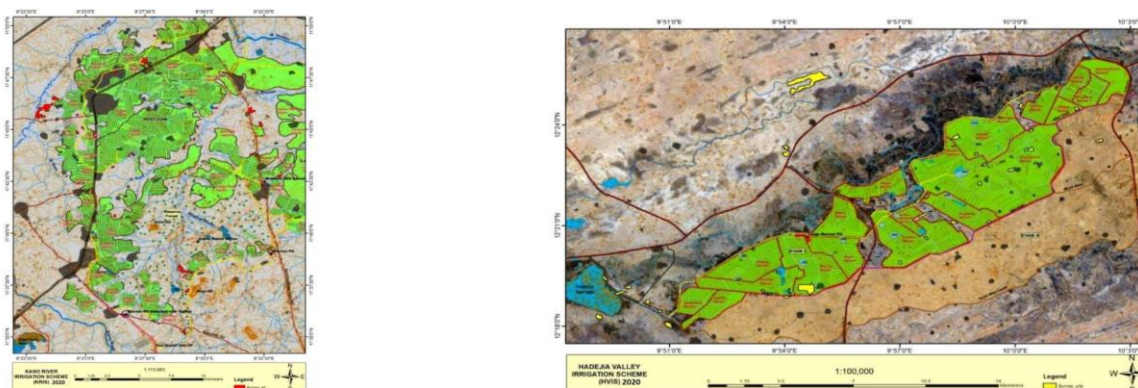


Figure 4: Borrow-pit distribution for the 2019 analytical reference-year inventory: (a) KRIS and (b) HVIS. Source: authors' field inventory and geospatial analysis. The analytical year used throughout the text, tables and statistical analysis is 2019

The largest change in the mapped inventory occurred between the 2009 and 2019 analytical reference years. KRIS added 13 mapped pits, while HVIS added 29. This interval overlaps with irrigation rehabilitation and continuing construction-material demand, but the spatial data do not attribute

individual pits to a particular project or operator. The observed pattern therefore, represents the cumulative mapped distribution of excavations detectable within the schemes and their immediate operational context.

Table 2: Average nearest Neighbour Results for Mapped Borrow-Pit Distributions

Scheme	Year	Pit count	NNR	z-score	Observed pattern
KRIS	1999	19	0.51	-4.07	Clustered
KRIS	2009	21	0.5	-4.33	Clustered
KRIS	2019	34	0.5	-5.45	Clustered
HVIS	1999	21	0.71	-2.57	Clustered
HVIS	2009	26	0.7	-2.80	Clustered
HVIS	2019	55	0.6	-5.80	Clustered

All six scheme-year combinations produced nearest-neighbour ratios below 1 and negative z-scores, indicating clustered rather than random or dispersed distributions. KRIS maintained a consistently strong degree of clustering, with NNR values of approximately 0.50 throughout the study period. Its z-score became more negative from -4.07 in 1999

to -5.45 in 2019 as the inventory expanded within already concentrated zones.

HVIS was also clustered, although its NNR values in 1999 and 2009 were closer to 1 than those of KRIS. By 2019, the HVIS ratio had fallen to 0.60 and its z-score to -5.80, indicating a stronger departure from complete spatial randomness. The source analysis reports observed mean

nearest-neighbour distances of approximately 1,966 m in KRIS and 2,015 m in HVIS for 1999. Together with the low ratios, these results indicate repeated excavation within

relatively limited operational catchments rather than even distribution across the schemes.

Table 3: Change in the Mapped Land Area Occupied by Borrow Pits

Scheme	1999 area	2009 area	2019 area	2019 share of scheme area
KRIS	43.3 ha	112.4 ha	180.2 ha	≈1.3% of 14,262.2 ha
HVIS	26.6 ha	≈32.0 ha	219.6 ha	≈1.8% of 12,500 ha

The mapped excavation footprint increased with the number of pits. In KRIS, mapped land occupied by borrow-pit polygons rose from approximately 43.3 ha in 1999 to 112.4 ha in 2009 and 180.2 ha in 2019. In HVIS, the mapped footprint increased from approximately 26.6 ha to 32.0 ha and then to 219.6 ha. The sharp 2009–2019 increase in HVIS indicates substantial growth in the mapped excavation area, arising from both additional mapped pits and enlargement of some mapped polygons. These values quantify land physically occupied by interpreted excavation footprints. They are not direct measurements of lost productive farmland, crop-yield reductions, or broader environmental damage. Conversely, they also exclude indirect disturbance such as access tracks, stockpiles, spoil placement, eroded margins and possible downstream sediment effects.

Discussion

Persistence and Intensification of Clustering

The results reveal a persistent spatial structure rather than a simple increase in the number of isolated mapped excavations. Borrow-pit counts and mapped footprint grew in both schemes, yet the nearest-neighbour ratios remained below 1 in every reference year. Under the ANN framework, the mapped pit centroids were spatially clustered within the fixed scheme boundaries. It does not establish why individual pits were located where they were. Operational factors such as haul distance, material suitability, road access and active work fronts provide plausible hypotheses for the observed concentration, but these require independent testing. Recent scholarship conceptualises aggregate extraction as a regional supply network linking demand, transport, geology, institutions and environmental effects rather than as a series of independent sites (Torres *et al.*, 2021). The KRIS and HVIS results are consistent with such a network perspective at the scheme scale.

The statistical trajectory is especially notable. KRIS remained strongly clustered while its mapped inventory increased from 19 to 34 pits. HVIS changed from a less concentrated mapped pattern in 1999 and 2009 to an NNR of 0.60 and a z-score of −5.80 in 2019, alongside a sharp rise in the mapped number and footprint of pits. This indicates stronger spatial concentration relative to complete spatial randomness, not a measured increase in environmental severity. Global reviews similarly show that construction-aggregate demand can produce spatially concentrated environmental and social pressures where cumulative effects are not incorporated into planning (Bendixen *et al.*, 2021; Torres *et al.*, 2021).

Clustering should nevertheless be interpreted as a screening signal, not proof of illegality or impact severity. Average Nearest Neighbour analysis is influenced by the size and shape of the study boundary and represents pit centroids rather than excavation geometry. Its management value lies in identifying priority zones for field inspection and cumulative assessment. Reviews of mining applications show that GIS and remote sensing are most effective when mapped change is combined with field verification and used to support

strategic and cumulative impact assessment (Werner *et al.*, 2019).

Implications for Irrigation Land and Infrastructure

The increase in mapped footprint represents direct land occupation or severe surface disturbance within the irrigation schemes. By 2019, approximately 180.2 ha in KRIS and 219.6 ha in HVIS were occupied by mapped borrow-pit polygons. These figures should not be equated directly with measured loss of productive farmland because the study did not classify the pre-excavation productivity, tenure or cropping status of every polygon. Nevertheless, scheme-wide percentages can conceal concentrated local land occupation near farms, canal reaches and drainage units. The mapped polygons also exclude access tracks, stockpiles, spoil disposal and eroded margins, so the footprint metric and productive-land-loss metric should be treated as distinct quantities.

The literature on sand and aggregate extraction identifies recurring pathways relevant to irrigation landscapes: removal of soil and sediment, altered topography, increased erosion, destabilised banks, modified surface-water pathways, and loss of productive land (Hackney *et al.*, 2020; Rentier & Cammeraat, 2022). The present study did not measure canal deformation or downstream sediment loads, and borrow pits beside irrigation works are not directly equivalent to in-channel sand mining. However, the documented mechanisms explain why clustered excavation near canals, drains, and river margins warrants geotechnical and hydrological investigation rather than relying on visual inspection alone. Persistence across successive image dates further suggests that some disturbances became long-lived landscape features. Where pits retain water, they may create drowning and disease-vector risks, while uncontrolled overflow can redirect runoff or discharge turbid water into drains. Where they remain dry, steep sides, exposed subsoil and compacted access routes can prolong erosion and delay agricultural recovery. These findings extend earlier evidence from Nigeria on abandoned borrow-pit hazards and inland sand extraction (Adedeji *et al.*, 2014; Nwachukwu *et al.*, 2017) by quantifying changes in inventory and footprint over two decades within functioning irrigation schemes.

Planning and Governance Implications

The clustered pattern is not inherently undesirable. Planned concentration may reduce haulage distance and avoid more sensitive land when material suitability, access, stability and restoration requirements are assessed in advance. The governance problem arises when approvals are issued pit by pit without considering the cumulative density and total disturbed area around canals, farms and settlements. Contemporary sand-governance literature therefore recommends moving from isolated site control to management of the entire material supply system, including demand reduction, alternative sources, traceability, monitoring and restoration (Bendixen *et al.*, 2021; Torres *et al.*, 2021).

For KRIS and HVIS, this requires a georeferenced material-source plan linked to engineering design and contract administration. Each authorised pit should have a unique identifier and records of location, ownership or operator, approval status, material type, approved dimensions and depth, extraction period, haul route, rehabilitation design, performance security and closure status. The register should be updated with high-resolution imagery and field verification. Spatial monitoring is particularly useful for detecting footprint expansion, comparing actual and approved boundaries, prioritising inspections and supporting cumulative impact assessment (Werner *et al.*, 2019).

Siting decisions should combine cumulative density with site-specific safeguards. Required controls include geotechnically justified setbacks from canal embankments, drains, roads, settlements and active farms; maximum depth and side-slope specifications; separate storage of topsoil; controlled drainage; erosion and sediment measures; safe access; and progressive rehabilitation. Restoration should be verified against measurable indicators of landform stability, soil replacement, vegetation establishment, drainage performance, and public safety criteria. Selected pits may be considered for controlled water storage or aquaculture only after separate assessments of water quality, seepage, flood interaction, tenure, community acceptance and long-term management responsibility.

Contribution and Remaining Research Gap

This study contributes evidence at a scale that remains underrepresented in the aggregate-extraction literature. Most global and river-focused studies examine material flows, channel response or broad environmental governance. By integrating historical inventories, polygon footprints and nearest-neighbour statistics for two large irrigation schemes, the analysis demonstrates how aggregate demand becomes embedded within agricultural infrastructure and how apparently small scheme-wide percentages can conceal concentrated local disturbance. It also provides a reproducible baseline against which future civil works contracts and rehabilitation performance can be assessed.

A significant evidence gap remains between the mapped distribution and causal impact. The present data do not identify the operator, extraction volume, pit depth, material destination, approval status or restoration history of every feature. They also do not quantify effects on crop yield, groundwater, canal seepage, flood routing, sediment delivery, household safety or the distribution of costs among affected farmers. Future research should combine seasonal field surveys, depth and volume measurements, soil and water testing, geotechnical inspection, farmer-level socioeconomic data and repeated high-resolution imagery. Before-and-after or matched-control designs would help distinguish the effects of excavation from other changes in irrigation performance and land management.

Study limitations

The study has four principal limitations. First, historical image resolution and seasonal differences in land cover may have caused omission of small, shallow or revegetated pits. Second, the ANN analysis used mapped centroids, so the statistic describes spacing among pit locations rather than the geometry of complete excavation footprints. Third, nearest-neighbour results are sensitive to the definition of the analysis boundary, although consistent scheme boundaries were used for temporal comparison. Fourth, spatial coincidence cannot identify the operator or establish whether a particular pit was created specifically for irrigation rehabilitation or for another

construction activity. Future research should combine permit records, contractor haulage information, high-resolution elevation surveys and farmer testimony with object-based or machine-learning change detection.

CONCLUSION

The mapped borrow-pit inventory in KRIS and HVIS expanded substantially between 1999 and 2019 and remained spatially clustered under the ANN analysis. The combined mapped inventory increased from 40 pits in 1999 to 89 pits in 2019. KRIS increased from 19 to 34 mapped pits, while HVIS increased from 21 to 55. Nearest-neighbour ratios remained below 1 for every scheme-year combination, with negative z-scores indicating statistically significant departure from complete spatial randomness under the stated analysis boundaries. By 2019, mapped borrow-pit footprints occupied approximately 180.2 ha in KRIS and 219.6 ha in HVIS. These results document mapped expansion and spatial concentration; they do not, by themselves, identify the causes of pit location, establish legal status or quantify environmental damage.

The findings support treating earth-material sourcing as a cumulative land-management and monitoring issue within the two irrigation schemes. Spatial concentration provides a basis for prioritising field inspection and rehabilitation planning, particularly where mapped pits occur near farms, drainage and hydraulic infrastructure. Sustainable irrigation rehabilitation should therefore integrate material-source planning with engineering design and environmental management. A georeferenced borrow-pit register, site-specific approval, risk-based setbacks, progressive rehabilitation and periodic imagery and field audits provide a practical framework for improving accountability. The effectiveness of these measures should be evaluated through field-based studies of pit depth, stability, hydrology, land productivity and rehabilitation outcomes.

- i. Create and maintain a GIS-based borrow-pit inventory for each irrigation scheme, and update it before, during, and after civil works contracts.
- ii. Require site-specific environmental and geotechnical assessment before excavation, covering material suitability, maximum depth, slope stability, drainage, and access and restoration design.
- iii. Establish enforceable setbacks from canal embankments, drains, roads, settlements and active farms based on site-specific stability and hydrological assessments.
- iv. Include measurable rehabilitation quantities, completion timelines, performance security and closure certification in construction contracts.
- v. Prioritise the highest-density clusters identified in the 2019 inventory for safety inspection, erosion control, backfilling, topsoil replacement and revegetation.
- vi. Use periodic high-resolution imagery and field verification to detect unauthorised excavation and compare actual pit footprints with approved boundaries.

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