Western European Journal of Modern Experiments and Scientific Methods
Volume 4, Issue 04 April 2026
https://westerneuropeanstudies.com/index.php/1
ISSN (E): 2942-1896 Open Access| Peer Reviewed

ENGINEERING SOLUTIONS FOR THE MODERNIZATION OF HIGHWAY DRAINAGE SYSTEMS

Professor Ganiyev Inomjon Gulomovich
Jizzakh Polytechnic Institute, Uzbekistan
E-mail: shavx.inomjon@gmail.com
Tog‘ayev Feruz Valijon o‘g‘li
2nd-year Master’s student, specialty “Automobile Roads and Airfields”
Jizzakh Polytechnic Institute, Uzbekistan

Abstract
Highway drainage systems are critical to pavement durability, embankment stability, hydraulic safety, and network reliability. In many existing road corridors, drainage infrastructure is under pressure from aging assets, increased runoff intensity, changing land use, and higher performance expectations. This paper provides a structured review of engineering solutions for the modernization of highway drainage systems, with emphasis on hydraulic upgrades, subsurface drainage improvement, sustainable drainage systems, permeable pavement applications, and digital asset-management tools. The review is based on official technical guidance and selected peer-reviewed studies. The results show that effective modernization should not be limited to enlarging pipes or replacing culverts; it should integrate conveyance, storage, infiltration, subgrade moisture control, inspection, and risk-based maintenance. The paper proposes an integrated engineering framework for selecting drainage modernization strategies and discusses its relevance for highway agencies operating under climate stress, maintenance backlogs, and life-cycle performance requirements.

Keywords: Highway drainage, drainage modernization, culverts, stormwater systems, subsurface drainage, permeable pavement, sustainable drainage systems, asset management.

1. Introduction

Drainage is one of the most decisive factors affecting long-term highway performance. Highway stormwater systems must collect, convey, and discharge runoff along the transportation right-of-way, while also protecting pavement layers, shoulders, embankments, and roadside assets from moisture-related damage. FHWA’s *Urban Drainage Design Manual (HEC-22)* presents highway drainage as a system-level engineering problem rather than a collection of isolated structures, and the AASHTO *Drainage Manual* similarly covers hydrology, channels, culverts, energy dissipators, storm drains, storage facilities, and pump stations as interconnected design elements [1], [2].

The urgency of drainage modernization has increased because many existing highways were designed for lower runoff volumes, older land-use conditions, and less demanding service expectations. At the same time, transport agencies increasingly operate within asset-management frameworks, where drainage is treated as a life-cycle infrastructure asset linked to pavement performance, geotechnical behavior, and operational resilience [3]. PIARC’s work on geotechnical structures for road asset management explicitly includes drainage and subgrade-related condition indicators, showing that drainage is fundamental not only to hydraulics but also to the structural reliability of the road corridor [3].

Modern drainage practice is also shifting from purely conveyance-based systems toward hybrid and resilient solutions. The 2025 UK national standards for Sustainable Drainage Systems (SuDS) address the design, maintenance, and operation of surface-water drainage systems and note that the standards can also inform retrofit work, not only new construction [4]. In parallel, EPA guidance describes permeable pavement as a stormwater best management practice that reduces runoff by allowing water to infiltrate through the pavement system while also providing pollutant filtration benefits [5]. These developments show that modernization today involves a broader engineering objective: not only faster runoff removal, but also better control of peak flow, infiltration, attenuation, and maintenance performance [4], [5].

Despite the strong technical literature on individual drainage components, there is still a shortage of integrated review studies that compare modernization strategies across hydraulic, geotechnical, sustainability, and asset-management dimensions within a single framework. This paper addresses that gap by synthesizing official guidance and selected peer-reviewed evidence into a comparative engineering structure that can support highway drainage upgrading decisions [1]-[10].

2. Methods

This study used a structured technical-review methodology. Sources were selected from official highway engineering manuals, drainage standards, and peer-reviewed publications relevant to highway drainage modernization. The core source set included FHWA HEC-22 (2024), FHWA HDS-5 on culvert design and rehabilitation, the AASHTO *Drainage Manual*, PIARC guidance on geotechnical structures and drainage within road asset management, the UK national SuDS standards, EPA guidance on permeable pavements, and recent journal articles on permeable asphalt, culvert inspection, and culvert renewal decision support [1]-[10].

The included sources were screened against four criteria: direct relevance to highway drainage modernization, engineering applicability to road drainage systems, explicit treatment of hydraulic or moisture-control performance, and usefulness for comparative evaluation. The selected materials were then organized into five modernization categories: conventional hydraulic upgrades, subsurface drainage improvement, culvert rehabilitation and renewal, sustainable/distributed drainage measures, and monitoring/asset-management tools. Each category was assessed qualitatively against hydraulic effectiveness, geotechnical benefit, sustainability contribution, implementation complexity, and compatibility with long-term maintenance planning.

To support engineering interpretation, the following integrated modernization score is proposed:

$$M_s=w_1H+w_2G+w_3S+w_4A \tag{1}$$

where M_s is the integrated modernization score, H is the hydraulic improvement score, G is the geotechnical reliability score, S is the sustainability score, A is the asset-management compatibility score, and w_1-w_4 are weighting coefficients selected according to project priorities. This formula is an author-defined analytical tool designed to compare modernization options consistently; it is not a code-prescribed design equation.

A second expression is used to describe hydraulic adequacy under modernization:

$$Q_{mod}\geq Q_{des}\, k_r \tag{2}$$

where Q_{mod} is the hydraulic capacity of the modernized system, Q_{des} is the design discharge, and kr is a resilience factor reflecting uncertainty related to blockage, aging, and future hydrologic stress. This framing is consistent with the systems-based approach emphasized in FHWA and AASHTO drainage guidance [1], [2].

3. Results

3.1. Conventional hydraulic upgrading remains essential

The first and most direct modernization pathway is the upgrading of conventional drainage elements: roadside ditches, inlets, storm sewers, culverts, headwalls, outlets, and pumping systems. FHWA HEC-22 emphasizes that storm-drain design must address collection, conveyance, and discharge together, while AASHTO's drainage guidance treats channels, culverts, energy dissipators, storm drains, storage, and pump stations as linked parts of one hydraulic system [1], [2]. This means that modernization should not be reduced to enlarging a pipe segment in isolation; corridor-level flow paths and upstream-downstream interactions must be checked as part of the redesign.

FHWA's HDS-5 further shows that culvert modernization now extends beyond hydraulic sizing to include culvert assessment, repair, rehabilitation, and renewal decisions [6]. The 2012 third edition added material on culvert assessment and repair/rehabilitation, indicating a clear shift from purely design-oriented practice toward condition-based modernization [6]. More recent ASCE work has taken this further: Jin et al. (2023) developed a culvert renewal selection approach that compares renewal techniques against host-culvert characteristics and multiple performance criteria, while Mohammadi and Asgari (2025) proposed a risk-based inspection framework that combines culvert condition prediction with prioritization [9], [10]. These studies suggest that culvert modernization is now increasingly data-driven and decision-supported, rather than only rule-based [9], [10].

3.2. Subsurface drainage is critical for pavement support

Surface drainage alone cannot protect a highway if moisture remains trapped within the pavement structure or subgrade. FHWA geotechnical pavement guidance notes that pavement performance depends on adequate support from geomaterials and that unsuitable subgrade conditions may require remediation [11]. PIARC likewise treats drainage as a key component in the condition of geotechnical road assets, including embankments, cuttings, and subgrade-related structures [3].

This makes subsurface drainage modernization one of the most important engineering interventions on moisture-sensitive roads. Common measures include longitudinal edge drains, underdrains, interceptor drains, drainage blankets, permeable subbase layers, and outlet rehabilitation. Earlier NCHRP and TRB documents on pavement subsurface drainage found that rapid removal of infiltrated water is one of the core objectives of edge-drain retrofits and that water in pavement base material is a major contributor to pavement failure [12], [13]. More recent literature continues to support this logic: Otto et al. (2020) found that drainage-related cross-sectional features influence low-volume road performance, and a 2025 review of pavement deterioration modeling explicitly states that drainage directly affects pavement structural performance by controlling moisture levels within and beneath the pavement [8], [14].

The relationship between drainage and pavement support can be summarized conceptually as:

$$Mr=f(\theta,S,D) \tag{3}$$

where M_r is resilient support modulus, θ is moisture condition, S is soil state, and D is drainage effectiveness. A_s D improves, harmful moisture retention is reduced and structural support becomes more stable. This is a conceptual representation, but it aligns with the geotechnical principle that pavement support is highly moisture-sensitive [11], [14].

3.3. Sustainable and distributed drainage solutions add resilience

A major trend in drainage modernization is the use of distributed or sustainable stormwater controls. The UK's 2025 SuDS standards place strong emphasis on design, maintenance, and operation, and they explicitly recognize their usefulness for retrofit contexts as well as new systems [4]. In engineering terms, this means that modernization can include bioswales, infiltration trenches, vegetated channels, filter strips, detention features, and controlled-release storage alongside conventional drainage assets [4].

The advantage of this approach is hydraulic diversification. Instead of moving all runoff immediately into pipes, the system may store, infiltrate, slow, and release water in stages. This reduces surcharge risk and lowers load on conventional storm drains. That strategy becomes especially valuable where pipe enlargement is spatially constrained or economically inefficient. EPA guidance on permeable pavement supports the same direction by describing green infrastructure as a way to reduce runoff volume and improve water-quality performance [5].

3.4. Permeable pavements are useful, but not universal

Permeable pavement systems are increasingly important in drainage modernization, especially for shoulders, rest areas, maintenance yards, parking zones, service roads, and lower-speed paved areas associated with transport infrastructure. EPA identifies permeable pavements as stormwater best management practices that allow runoff to infiltrate through the pavement and reduce runoff while filtering pollutants [5]. Sousa et al. (2024) further report that permeable asphalt pavement can be effective for stormwater management and flood-risk reduction, while also noting that clogging remains one of the principal long-term performance constraints [7].

This is a critical point for engineering design: permeable pavements are not plug-in replacements for all road surfaces. Their modernization value depends on sediment control, maintenance access, layer design, infiltration conditions, and the ability to prevent progressive clogging. A 2025 field experiment on urban permeable pavement reported that runoff reduction performance declined over time without cleaning, illustrating the need for maintenance-aware design [15]. For highway agencies, this means permeable systems should be selected where their hydrologic and maintenance conditions are genuinely suitable, not merely because they are environmentally attractive [15].

A simplified runoff-balance expression for these systems is:

$$V_r=PA-(I+S+D_o) \tag{4}$$

where V_r is residual surface runoff, P is rainfall depth, A is contributing area, I is infiltrated volume, S is temporarily stored volume, and D_o is controlled outflow. Modernization measures that increase III and SSS reduce direct runoff pressure on downstream drainage assets [5], [7].

3.5. Monitoring and asset management are no longer optional

A modern drainage system cannot rely only on reactive maintenance. PIARC's condition-indicator framework and FHWA's systems-based drainage guidance both support condition-driven management rather than failure-driven response [1], [3]. In practical terms, this includes drainage inventories, GIS-based mapping, CCTV inspections, culvert condition records, blockage-risk screening, flood-point history, and sensor-based monitoring at critical locations [1], [3], [9], [10].

Recent ASCE studies reinforce this direction. The Utah case study by Mohammadi and Asgari (2025) used hybrid XGBoost and risk-based prioritization to support culvert inspection and condition assessment, while the culvert renewal selection work by Jin et al. (2023) shows how decision tools can guide technique selection more systematically [9], [10]. These studies are important because they move drainage modernization beyond physical reconstruction alone and toward predictive management.

The operational logic may be expressed as:

$$P_f=f(B, C, A, H) \tag{5}$$

where P_f is drainage failure probability, B is blockage state, C is capacity deterioration, A is asset age/condition, and H is hydrologic loading severity. Monitoring-based modernization attempts to reduce P_f by identifying adverse changes before hydraulic or structural failure occurs.

4. Discussion

The review shows that no single modernization strategy is universally optimal. Conventional hydraulic enlargement is indispensable where flooding risk is already high, but it may not solve performance problems driven by subgrade saturation or trapped pavement moisture. Conversely, subsurface drainage interventions may deliver major structural benefits while leaving surface conveyance bottlenecks unresolved. Sustainable drainage and permeable pavement systems can improve resilience and runoff control, but their success depends on soil conditions, available space, and maintenance discipline [1]-[8].

For this reason, the most rational engineering strategy is usually hybrid. On many highways, the best outcome will come from combining selective conveyance upgrades with subsurface drainage improvement and risk-based maintenance planning. Distributed stormwater controls can then be added where right-of-way, hydrology, and maintenance capability make them feasible. This layered modernization logic is more consistent with current engineering evidence than any single-solution approach.

A further implication is that management transformation can begin before large-scale construction. Even when major drainage reconstruction is financially constrained, agencies can still improve performance by building inventories, prioritizing high-risk culverts and flood-prone sections, and introducing condition-based maintenance rules. That step alone can reduce avoidable failures and provide a better basis for phased investment [3], [9], [10].

For regions such as Uzbekistan, the engineering lesson is clear: drainage modernization should not be standardized as a single national template for all corridors. Irrigated plains with shallow groundwater, urbanizing arterial roads, foothill sections subject to erosion and debris, and heavily trafficked freight corridors require different drainage modernization priorities. A differentiated regional approach is therefore more defensible than a uniform one. This conclusion is an inference drawn from the reviewed international guidance and literature rather than a direct statement from any single source.

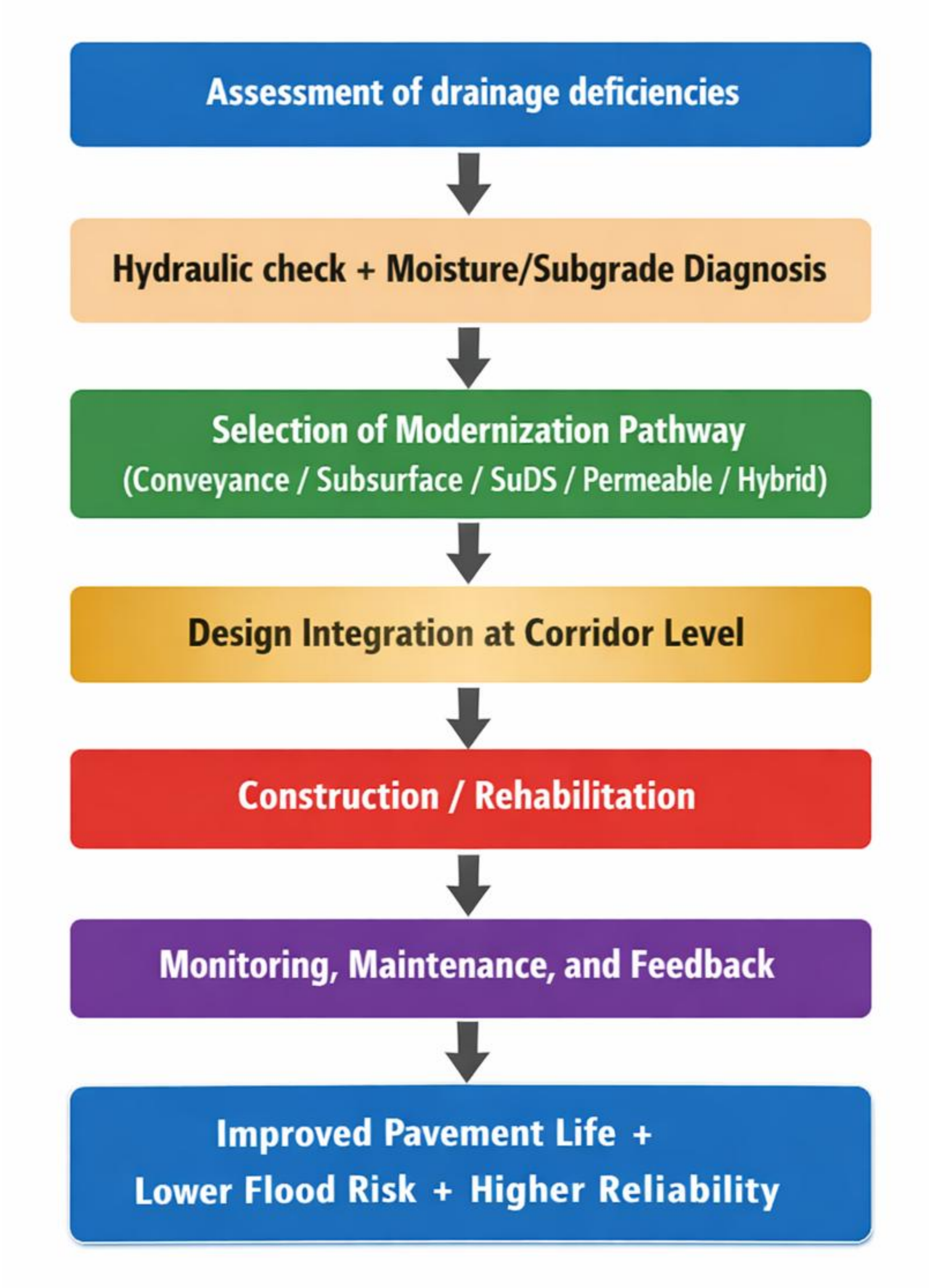
5. Table

Table 1. Multi-criteria assessment of drainage modernization strategies

Strategy	Hydraulic effectiveness	Geotechnical benefit	Sustainability contribution	Monitoring compatibility	Overall priority
Storm-sewer and culvert enlargement	5	2	2	4	4
Edge drains and underdrains	3	5	3	4	4
Drainage blanket / permeable subbase	3	5	3	3	4
SuDS / distributed controls	4	3	5	3	4
Permeable pavement for auxiliary areas	3	2	5	3	3
Digital monitoring and GIS-based asset management	2	3	4	5	4

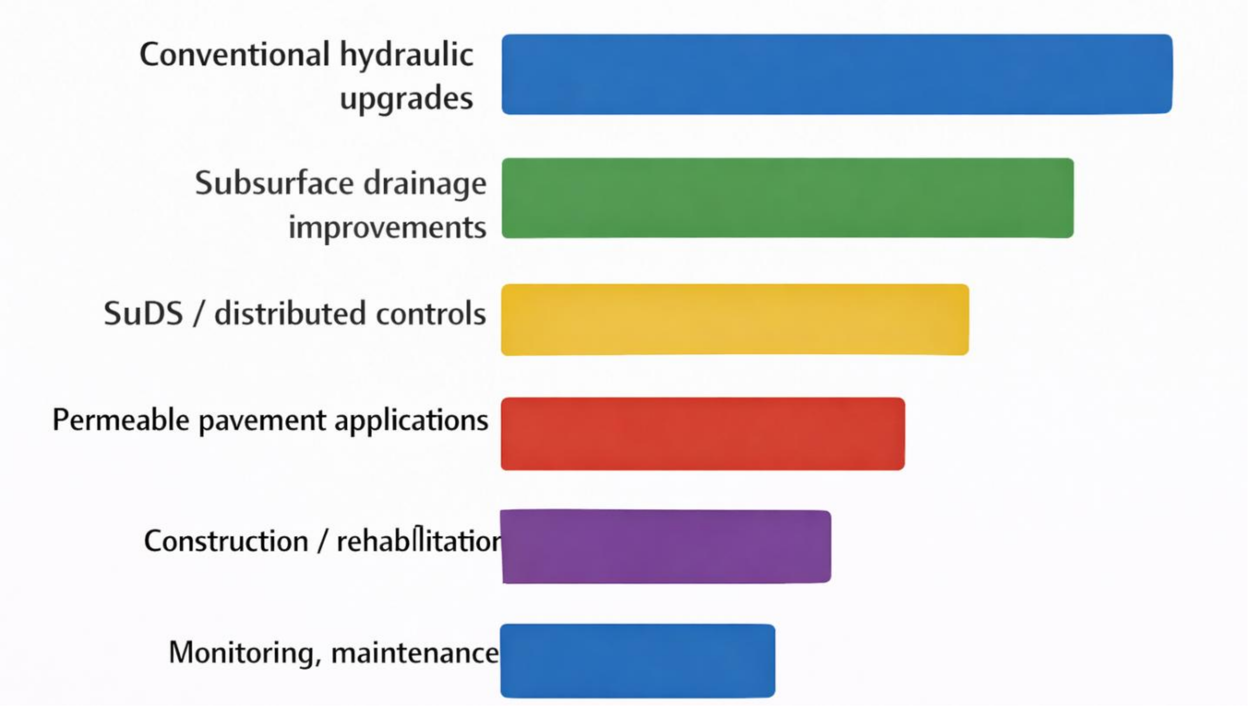
Note. Scores are on a 1-5 relative scale. The matrix is an author-developed engineering synthesis derived from the comparative evidence in [1]-[10].

6. Figure



This figure is an author-developed synthesis based on [1]-[10].

7. Diagram



Interpretation.
This is a qualitative diagram, not a statistical graph. It visualizes the relative prominence of different modernization strategies in the reviewed guidance and studies, where hydraulic upgrading and monitoring remain central, while subsurface drainage and distributed stormwater controls are increasingly important [1]-[10].

8. Conclusion

The critical review shows that modernization of highway drainage systems should be treated as an integrated engineering problem involving hydraulics, pavement support, geotechnical reliability, sustainability, and asset management. Official guidance consistently supports a systems-based view, and recent peer-reviewed studies strengthen the case for decision tools, condition prediction, and maintenance-aware design [1]-[10].

The most effective modernization strategies are hybrid rather than singular. Enlarging pipes or replacing culverts is often necessary, but long-term performance also depends on controlling subsurface moisture, using distributed stormwater measures where appropriate, and implementing monitoring-based maintenance. Permeable pavements and SuDS can add resilience, but only under conditions that support their hydraulic function and maintenance requirements [4], [5], [7], [15].

Scientifically, the paper’s main contribution is the integrated comparative framework that evaluates drainage modernization options across hydraulic, geotechnical, sustainability, and asset-management dimensions. Practically, it supports the view that highway drainage modernization should be prioritized not as isolated repair work, but as a structured resilience strategy for long-life road performance.

9. Limitations

This paper is based primarily on official guidance documents and selected peer-reviewed studies rather than on one unified field dataset for a specific highway network. The proposed scoring matrix and analytical expressions are interpretive tools intended to support engineering synthesis, not substitutes for site-specific hydraulic modeling, pavement investigation, or formal design standards. The conclusions should therefore be read as a strategic technical framework rather than a project-level design prescription.

References

[1] Federal Highway Administration. *Urban Drainage Design Manual (HEC-22), Fourth Edition*. U.S. Department of Transportation, 2024.
[2] American Association of State Highway and Transportation Officials. *AASHTO Drainage Manual*. Washington, DC, 2014.
[3] PIARC. *Indicators Representative of the Condition of Geotechnical Structures for Road Asset Management*. World Road Association, 2008.
[4] UK Government. *National Standards for Sustainable Drainage Systems (SuDS)*, 2025.
[5] U.S. Environmental Protection Agency. *Permeable Pavement: Stormwater Best Management Practice*.
[6] Schall, J. D., Thompson, P. L., and others. *Hydraulic Design of Highway Culverts (HDS-5), Third Edition*. FHWA, 2012.
[7] Sousa, M., et al. "Permeable Asphalt Pavements (PAP): Benefits, Clogging, Maintenance, and Future Prospects." *Materials*, 2024.
[8] Famewo, B. G., et al. "A Review of Pavement Performance Deterioration Modeling." *Symmetry*, 2025.
[9] Mohammadi, P., Asgari, S., et al. "Culvert Inspection Framework Using Hybrid XGBoost and Risk-Based Prioritization: Utah Case Study." *Journal of Construction Engineering and Management*, 2025.
[10] Jin, H., et al. "Decision-Making Guidance for the Optimal Selection of Culvert Renewal Techniques." *Journal of Pipeline Systems Engineering and Practice*, 2023.
[11] Federal Highway Administration. *Geotechnical Aspects of Pavements*. U.S. Department of Transportation.
[12] Transportation Research Board. *Performance of Pavement Subsurface Drainage*. NCHRP Digest.
[13] Transportation Research Board. *NCHRP Research Results Digest 268: Edge Drains*.
[14] Otto, A., et al. "The Impact of Drainage on the Performance of Low Volume Sealed Roads." *Sustainability*, 2020.
[15] Chen, C. F., et al. "A 4-Year Field Experiment on an Urban Permeable Pavement System." *Land*, 2025.