East African Journal of Engineering, Volume 8, Issue 2, 2025
Article DOI: https://doi.org/10.37284/eaje.8.2.3995

East African Journal of Engineering
eaje.eanso.org
Volume 8, Issue 2, 2025
Print ISSN: 2707-5389 | Online ISSN: 2707-5397
Title DOI: https://doi.org/10.37284/2707-5397

EAST AFRICAN NATURE & SCIENCE ORGANIZATION

Original Article

Development of Maintenance Management Model for Enhancement Performance of Culverts: A Case of Kinondoni District Council

Edwin Kabwoto[1] & Dr. Blausius Ngayakamo, PhD[1]*

[1] Dar es Salaam Institute of Technology, P. O. Box 2958, Dar es Salaam, Tanzania.
[*] Author for Correspondence Email: ekabwoto@yahoo.co.uk

Article DOI : https://doi.org/10.37284/eaje.8.2.3995

Publication Date:

15 November 2025

Keywords:

Culvert Maintenance, Infrastructure Management, Multiple Regression Model, Performance Assessment, Kinondoni District Council, Urban Drainage Systems

ABSTRACT

Culverts are vital components of urban drainage infrastructure, yet many suffer from poor performance due to inadequate maintenance practices. This study developed a comprehensive maintenance management model to enhance culvert performance in Kinondoni District Council, Tanzania. Using a mixed-methods research approach, 194 infrastructure professionals were surveyed to assess factors affecting culvert performance through Relative Importance Index (RII) analysis. A multiple regression model was developed and validated to predict culvert condition based on seven critical factors: structural integrity, hydraulic capacity, blockage clearance, desilting, climate change adaptation, erosion protection, and maintenance practices. The regression model demonstrated strong predictive capability with $R = 0.780$, explaining 60.8% of variance in culvert performance ($F = 41.837$, $p < 0.001$). Field validation across four representative culverts showed performance scores ranging from 54.7% (good condition) to 20.6% (poor condition), confirming the model's discriminatory capability. The RII analysis revealed structural integrity (84.3%) and hydraulic capacity (83.4%) as the most critical factors affecting culvert performance. The study concludes that systematic, evidence-based maintenance management significantly improves infrastructure performance and resource allocation efficiency. The developed model provides practitioners with quantitative tools for prioritising interventions and optimising maintenance strategies, ultimately extending culvert lifespan and enhancing drainage system reliability in urban environments.

APA CITATION

Kabwoto, E. & Ngayakamo, B. (2025). Development of Maintenance Management Model for Enhancement Performance of Culverts: A Case of Kinondoni District Council. *East African Journal of Engineering*, *8*(2), 399-410. https://doi.org/10.37284/eaje.8.2.3995

CHICAGO CITATION

Kabwoto, Edwin and Blausius Ngayakamo. 2025. "Development of Maintenance Management Model for Enhancement Performance of Culverts: A Case of Kinondoni District Council". *East African Journal of Engineering* 8 (2), 399-410. https://doi.org/10.37284/eaje.8.2.3995.

Article DOI: https://doi.org/10.37284/eaje.8.2.3995

HARVARD CITATION

Kabwoto, E. & Ngayakamo, B. (2025) "Development of Maintenance Management Model for Enhancement Performance of Culverts: A Case of Kinondoni District Council", *East African Journal of Engineering*, 8(2), pp. 399-410. doi: 10.37284/eaje.8.2.3995.

IEEE CITATION

E. Kabwoto & B. Ngayakamo "Development of Maintenance Management Model for Enhancement Performance of Culverts: A Case of Kinondoni District Council" *EAJE*, vol. 8, no. 2, pp 399-410, Nov. 2025.

MLA CITATION

Kabwoto, Edwin & Blausius Ngayakamo. "Development of Maintenance Management Model for Enhancement Performance of Culverts: A Case of Kinondoni District Council" *East African Journal of Engineering*, Vol. 8, no. 2, Nov. 2025, pp. 399-410, doi:10.37284/eaje.8.2.3995.

INTRODUCTION

Culverts serve as indispensable components of urban infrastructure systems, facilitating effective stormwater drainage and maintaining road network functionality in rapidly urbanising areas like Kinondoni District Council. These structures play a critical role in cross-drainage management, preventing water accumulation that could otherwise compromise road integrity, disrupt transportation networks, and pose significant safety risks to communities (Wang et al., 2023). In developing regions experiencing rapid urban growth, culverts become increasingly vital for managing the impacts of expanded impervious surfaces that amplify runoff volumes and necessitate robust drainage infrastructure.

Despite their critical importance, culverts in Kinondoni District face substantial performance challenges that threaten infrastructure resilience and public safety. A significant portion of the district's 377 documented culverts exhibit poor conditions, including structural deterioration, debris blockages, and sedimentation that restricts water flow capacity. These challenges are compounded by environmental factors such as intense rainfall events and urban runoff, which increase hydraulic loads and accelerate erosion around culvert structures (Edward, 2022). Such conditions frequently result in flooding, road damage, and hazardous conditions for road users, particularly affecting vulnerable low-lying areas within the district.

Current maintenance practices in Kinondoni District are predominantly reactive, focusing on addressing culvert failures after they occur rather than preventing problems through systematic intervention. This approach is both inefficient and costly, leading to premature infrastructure deterioration and increased long-term maintenance expenses. The district's culvert inventory management system suffers from incomplete and inconsistent data, lacking essential information such as construction dates, accurate location coordinates, and detailed maintenance histories (Schoeman, 2019). This data deficiency hampers effective maintenance planning, resource allocation, and evidence-based decision-making.

The absence of a comprehensive maintenance management model has contributed to accelerated culvert deterioration, elevated flood risks, and compromised public safety throughout the district. Research demonstrates that systematic maintenance approaches can reduce infrastructure lifecycle costs by up to 50% compared to reactive strategies while significantly improving performance outcomes (Meegoda & Zou, 2015). A structured maintenance management model incorporating predictive tools, environmental factors, and standardised protocols is essential for addressing these deficiencies and enhancing infrastructure longevity.

This study addresses the critical need for evidence-based culvert maintenance management in Kinondoni District Council through the development of a comprehensive predictive model. The research objectives include identifying key

Article DOI: https://doi.org/10.37284/eaje.8.2.3995

factors affecting culvert performance, developing a quantitative maintenance management model, and validating the model's practical applicability through field assessments. By establishing a systematic framework for culvert condition assessment and maintenance prioritisation, this research provides infrastructure managers with practical tools to optimise resource allocation, reduce flood risks, and enhance the safety and reliability of the district's drainage infrastructure network.

LITERATURE REVIEW

Culvert Infrastructure and Performance Assessment

Culverts represent critical hydraulic structures that enable water conveyance beneath transportation infrastructure while maintaining structural integrity under various loading conditions. These structures must accommodate both hydraulic requirements for water flow and structural demands from traffic loads, soil pressures, and environmental stresses (Wang et al., 2023). Performance assessment of culverts requires systematic evaluation of multiple parameters, including structural condition, hydraulic capacity, and operational functionality.

Contemporary approaches to culvert condition assessment emphasise standardised protocols that evaluate physical deterioration, functional capacity, and maintenance requirements. Assessment methodologies typically employ condition rating systems that categorise infrastructure into performance levels ranging from excellent to critical condition, enabling systematic prioritisation of maintenance interventions (Zhang et al., 2024). These standardised approaches facilitate consistent evaluation across different infrastructure assets and support evidence-based resource allocation decisions.

Environmental factors significantly influence culvert performance and deterioration rates. Climate conditions, including precipitation intensity, temperature variations, and soil characteristics, affect material degradation processes and structural stability. Research by Aramburu Paucar et al. (2024) highlights how changing precipitation patterns and extreme weather events increasingly challenge existing culvert capacity and necessitate adaptive management approaches that consider future climate scenarios.

Factors Affecting Culvert Performance

Extensive research has identified multiple categories of factors that influence culvert performance throughout their operational lifespan. Structural factors include material integrity, foundation stability, and load-bearing capacity, which determine the fundamental capability of culverts to maintain functionality under operational stresses. Deterioration of structural elements can lead to catastrophic failure, posing significant risks to transportation networks and public safety (Wysokowski, 2019).

Hydraulic factors encompass flow capacity, inlet and outlet conditions, and sediment management, which collectively determine the effectiveness of water conveyance. Inadequate hydraulic capacity leads to overtopping, upstream flooding, and potential structural damage during rainfall events. Sedimentation and debris accumulation progressively reduce effective flow area, necessitating regular maintenance interventions to preserve functionality (Zou, 2015).

Operational factors include maintenance practices, inspection protocols, and resource allocation strategies that influence long-term performance outcomes. Research demonstrates that proactive maintenance approaches significantly outperform reactive strategies in terms of cost-effectiveness and performance preservation. However, the quality and appropriateness of maintenance activities are critical determinants of success, as inappropriate

Article DOI: https://doi.org/10.37284/eaje.8.2.3995

interventions can potentially cause damage rather than improvement (Montgomery et al., 2021).

Maintenance Management Models and Approaches

Multiple regression modelling has emerged as a preferred approach for quantifying relationships between maintenance factors and infrastructure performance outcomes. This statistical methodology enables the development of predictive equations that incorporate multiple variables while providing statistical validation through measures such as R^2, F-tests, and coefficient significance testing. The approach offers advantages in terms of quantitative precision and empirical validation compared to subjective assessment methods (Montgomery et al., 2021).

Alternative modelling approaches include Analytical Hierarchy Process (AHP) and expert systems, each offering distinct capabilities for different applications. AHP provides structured decision-making frameworks based on expert judgment but offers limited statistical validation capabilities. Expert systems can incorporate complex decision rules but require extensive knowledge engineering and may lack transparency in decision processes.

Contemporary maintenance management increasingly emphasises predictive approaches that anticipate infrastructure deterioration and optimise intervention timing. Predictive models enable proactive maintenance planning, efficient resource allocation, and improved performance outcomes compared to reactive approaches. Integration of these models with digital management systems enhances accessibility and facilitates systematic implementation across infrastructure networks (Cunningham & Miller, 2020).

Research Gaps

While existing literature provides valuable insights into culvert maintenance and infrastructure management, several critical gaps remain unaddressed, particularly in developing country contexts. First, most existing maintenance models have been developed for developed countries with different environmental conditions, resource availability, and institutional capacities. The applicability of these models to tropical environments with intense rainfall patterns and limited maintenance resources remains unexplored. Second, previous studies have focused predominantly on either structural or hydraulic aspects of culvert performance in isolation, without developing integrated models that simultaneously consider multiple interacting factors. Third, there is limited empirical validation of maintenance management models in real-world settings, with most studies relying on theoretical frameworks rather than field-tested applications. Fourth, the specific challenges of urban drainage infrastructure in rapidly growing African cities, where informal settlements and inadequate planning compound drainage problems, have received insufficient attention in the academic literature. Finally, quantitative tools that enable infrastructure managers in resource-constrained environments to prioritise maintenance interventions based on objective performance metrics are notably absent from current practice. This study addresses these gaps by developing and validating a comprehensive, context-specific maintenance management model tailored to the unique challenges of Kinondoni District Council, providing practical tools for evidence-based decision-making in developing urban environments.

METHODOLOGY

Research Design and Approach

This research employed a mixed-methods design integrating quantitative analysis of culvert performance factors with qualitative insights from infrastructure professionals. The approach combined statistical modelling techniques with field observations to ensure a comprehensive understanding of maintenance challenges and the

Article DOI: https://doi.org/10.37284/eaje.8.2.3995

practical applicability of developed solutions. A pragmatic research philosophy guided the study, emphasising practical outcomes and solution-oriented approaches relevant to local infrastructure management needs.

Study Area

The research was conducted in Kinondoni District Council, Dar es Salaam Region, Tanzania, encompassing coordinates 39.07962°E to 39.28807°E longitude and 6.57760°S to 6.82192°S latitude. The study area was selected for its representative urban infrastructure challenges and substantial culvert inventory requiring systematic management. The district's 377 documented culverts provided a comprehensive population for developing and validating maintenance management approaches.

Study Population and Sample Size

The study population comprised infrastructure professionals from various organisations involved in culvert design, construction, and maintenance within Kinondoni District. Participants represented TARURA (Tanzania Rural and Urban Roads Agency), Kinondoni Municipal Council, TANROADS (Tanzania National Roads Agency), consulting firms, and construction contractors. This diverse stakeholder group (N=377 professionals) ensured comprehensive perspectives on maintenance challenges and system requirements.

Sample size determination followed Yamane's formula for finite populations:

$$n = N / (1 + N(e)^2) \quad (1)$$

Where:

- n = Required sample size
- N = Total population (377 infrastructure professionals)
- e = Margin of error (0.05)

Calculation: $n = 377 / (1 + 377(0.05)^2)$ $n = 377 / (1 + 0.9425)$ $n = 377 / 1.9425$ $n = 194$ respondents

Table 1: Sample Distribution

Category	Population	Sample Size	Percentage
Infrastructure Professionals	377	194	100%

Note. Stratified random sampling was employed to ensure representative coverage across organisational categories.

Sampling Strategy

Stratified random sampling was employed to ensure representative coverage across different organisational categories and professional roles. This approach guaranteed diverse perspectives while maintaining statistical validity for model development and validation.

Data Collection Methods

Primary data collection utilised structured questionnaires employing 4-point Likert scales to assess 16 potential factors affecting culvert performance. The questionnaire design incorporated established survey methodology principles and underwent pre-testing to ensure clarity and relevance. Semi-structured interviews with key stakeholders provided qualitative insights into maintenance practices, challenges, and improvement opportunities.

Field observations documented actual culvert conditions across the district, providing empirical data for model validation. Systematic inspection protocols captured structural conditions, hydraulic performance, and maintenance requirements using standardised assessment criteria. Geographic positioning systems enabled precise location

Article DOI: https://doi.org/10.37284/eaje.8.2.3995

documentation for spatial analysis and future monitoring.

Secondary data sources included municipal infrastructure records, maintenance histories, construction documentation, and meteorological data relevant to drainage performance. These sources provided contextual information and historical trends essential for a comprehensive understanding of maintenance challenges.

Data Analysis Framework

Quantitative analysis employed the Relative Importance Index (RII) methodology to rank factors based on stakeholder assessments. The RII calculation formula was:

$$RII = \sum W \times X/(A \times N) \quad (2)$$

Where:

- W = Weight assigned by respondents
- X = Frequency of each response
- A = Highest weight (4 in this survey)
- N = Total number of respondents (194)

Multiple regression analysis was conducted using SPSS software to develop predictive models quantifying relationships between significant factors and culvert performance. Statistical validation included assessment of R^2, adjusted R^2, F-statistics, and individual coefficient significance testing to ensure model robustness and practical utility. Model validation utilised field data from representative culverts across different condition categories. Performance predictions were compared against actual field assessments to evaluate model accuracy and identify potential calibration requirements.

FINDINGS

Factor Assessment and Prioritisation

Analysis of 16 potential factors affecting culvert performance revealed a distinct bimodal distribution, with seven factors achieving high significance levels (RII ≥ 0.765) while nine factors scored significantly lower (RII ≤ 0.464). This clear separation indicates strong stakeholder consensus regarding maintenance priorities and provides focused guidance for resource allocation decisions.

Table 2: Relative Importance Index of Factors Affecting Culvert Performance

Rank	Factor	RII Value	RII (%)	Significance Level
1	Structural Integrity	0.843	84.3%	Most Significant
2	Hydraulic Capacity	0.834	83.4%	Most Significant
3	Blockage Clearance	0.789	78.9%	Most Significant
4	Desilting	0.785	78.5%	Most Significant
5	Climate Change Adaptation	0.777	77.7%	Most Significant
6	Erosion Protection	0.775	77.5%	Most Significant
7	Insufficient Maintenance	0.765	76.5%	Most Significant
8	Traffic Loading	0.464	46.4%	Less Significant
9	Environmental Factors	0.452	45.2%	Less Significant
10	Soil Condition	0.451	45.1%	Less Significant
11	Age and Wear	0.447	44.7%	Not Significant
12	Vegetation Growth	0.446	44.6%	Not Significant
13	Installation Quality	0.441	44.1%	Not Significant
14	Backwater Effect	0.438	43.8%	Not Significant
15	Material Design	0.430	43.0%	Not Significant
16	Culvert Design	0.423	42.3%	Not Significant

Article DOI: https://doi.org/10.37284/eaje.8.2.3995

Structural Integrity emerged as the most critical factor (RII = 0.843), reflecting stakeholder recognition that fundamental structural soundness forms the foundation of culvert functionality. Hydraulic Capacity ranked second (RII = 0.834), highlighting the primary functional purpose of culverts as water conveyance structures. The cluster of operational and environmental factors achieving the most significant ratings (blockage clearance, desilting, climate change adaptation, erosion protection, and maintenance practices) represents the second tier of priority factors.

Multiple Regression Model Development

Multiple regression analysis using the seven highest-ranked factors as predictors yielded a robust predictive model with strong statistical validity. The model achieved excellent correlation (R = 0.780) and substantial explanatory power (R^2 = 0.608), indicating that the selected factors explain approximately 61% of the variance in culvert performance.

Table 3: Model Summary and Statistical Validation

Model Statistics	Value	Interpretation
R	0.780	Strong correlation
R Square	0.608	61% variance explained
Adjusted R Square	0.594	Robust predictive power
Std. Error of Estimate	0.487	Acceptable accuracy
F-statistic	41.837	Highly significant
Significance	0.000*	$p < 0.001$

Note. *Significant at $p < 0.05$

The ANOVA results confirmed overall model significance ($F = 41.837$, $p < 0.001$), validating the predictive relationships between factors and culvert performance. The adjusted R^2 value of 0.594 confirmed model robustness when accounting for the number of predictors.

Table 4: Regression Coefficients and Statistical Significance

Variable	Unstandardized Coefficient	Standardized Coefficient	t-value	Significance
(Constant)	0.03	-	4.556	0.000*
Structural Integrity	0.029	0.311	4.581	0.000*
Hydraulic Capacity	0.019	0.253	3.947	0.000*
Blockage Clearance	0.012	0.217	3.596	0.001*
Desilting	0.045	0.192	3.111	0.002*
Climate Change Adaptation	0.051	0.168	2.843	0.005*
Erosion Protection	0.020	0.152	2.276	0.024*
Insufficient Maintenance	-0.020	-0.126	2.224	0.027*

Note. *Significant at $p < 0.05$

The regression equation derived from the analysis is:

Culvert Performance = 0.03 + 0.029(Structural Integrity) + 0.019(Hydraulic Capacity) + 0.012(Blockage Clearance) + 0.045(Desilting) + 0.051(Climate Change Adaptation) + 0.020(Erosion Protection) - 0.020(Insufficient Maintenance) (3)

Article DOI: https://doi.org/10.37284/eaje.8.2.3995

Climate Change Adaptation demonstrated the highest positive coefficient (0.051), emphasising the critical importance of future-proofing infrastructure against changing precipitation patterns and extreme weather events. Desilting showed the second-highest positive coefficient (0.045), highlighting the substantial performance benefits achievable through regular sediment removal programs. The negative coefficient for Insufficient Maintenance (-0.020) indicates that culverts requiring more frequent maintenance are inherently problematic, suggesting that maintenance frequency serves as an indicator of underlying issues.

Model Validation and Performance Assessment

Model validation using four representative culverts across Kinondoni District demonstrated excellent discriminatory capability and practical applicability. Performance scores ranged from 54.7% (good condition) to 20.6% (poor condition), effectively capturing the diversity of culvert conditions.

Table 5: Model Validation Results

Culvert Name	Performance Score	Performance Category	Classification	Action Required
Boko Magereza	54.7%	45-65%	Good	Routine Maintenance
Makurinza Box	50.0%	45-65%	Good	Routine Maintenance
Mbopo Box	39.1%	25-45%	Fair	Schedule Repair
RTD II	20.6%	<25%	Poor	Major Rehabilitation

Note. Performance Classification: Excellent (65-100%), Good (45-65%), Fair (25-45%), Poor (<25%)

RTD II culvert, with its 20.6% performance rating, demonstrated critical infrastructure challenges requiring immediate major rehabilitation. Mbopo Box and Makurinza Box culverts achieved intermediate performance ratings (39.1% and 50.0% respectively), representing categories where targeted improvements can yield significant benefits. Boko Magereza culvert achieved the highest performance rating (54.7%), providing a benchmark for best practices in culvert management.

DISCUSSION

Factor Prioritisation and Consensus

The research findings provide significant insights into culvert maintenance management challenges and opportunities in developing urban contexts. The clear factor hierarchy identified through RII analysis offers practical guidance for maintenance prioritisation and resource allocation, with structural integrity (84.3%) and hydraulic capacity (83.4%) emerging as paramount concerns. These findings align with Wang et al. (2023), who emphasised that culverts must simultaneously accommodate hydraulic requirements and structural demands. However, the current study extends this understanding by quantifying the relative importance of these factors in a developing country context, where resource constraints make prioritisation critical.

The bimodal factor distribution demonstrates strong stakeholder consensus regarding maintenance priorities, facilitating evidence-based decision-making about resource allocation. This consensus is particularly noteworthy given the diverse stakeholder group, suggesting that maintenance professionals across different organisations share a common understanding of critical challenges. This finding contrasts with Schoeman (2019), who

Article DOI: https://doi.org/10.37284/eaje.8.2.3995

reported fragmented approaches to infrastructure management in developing countries, suggesting that targeted engagement can build shared understanding even in resource-constrained environments.

Predictive Model Performance and Validation

The robust predictive model (R^2 = 0.608) demonstrates the feasibility of quantitative approaches to maintenance management in developing contexts. This explanatory power is comparable to models developed by Meegoda and Zou (2015), who achieved R^2 values of 0.62 in their infrastructure sustainability assessment, validating the applicability of multiple regression approaches across different contexts. However, the current study extends previous work by integrating climate change adaptation factors, reflecting emerging challenges in tropical urban environments.

The model's statistical significance ($F = 41.837$, $p < 0.001$) and practical validation across diverse culvert conditions confirm its utility for both diagnostic assessment and maintenance planning. Unlike previous studies that relied primarily on theoretical frameworks, this research demonstrates field-tested applicability through validation across culverts ranging from good to poor condition. The consistent relationship patterns align with theoretical expectations while providing quantifiable guidance for intervention prioritisation.

Climate Change Adaptation and Environmental Factors

Climate change adaptation emerged as the most influential positive factor (coefficient = 0.051), reflecting growing recognition that infrastructure must be prepared for changing environmental conditions. This finding resonates with Aramburu Paucar et al. (2024), who highlighted how changing precipitation patterns increasingly challenge existing drainage capacity. However, the current study uniquely quantifies this relationship, demonstrating that climate adaptation measures have the strongest marginal impact on culvert performance among all factors examined.

This finding has particular relevance for tropical regions experiencing intensifying precipitation patterns and extreme weather events. Unlike Wysokowski (2019), who focused primarily on structural deterioration in temperate climates, this study demonstrates that environmental adaptation represents the most critical intervention area in tropical urban contexts. This suggests that design standards and maintenance protocols must be fundamentally reconsidered for cities experiencing rapid climate change impacts.

Maintenance Practices and Operational Challenges

The unexpected negative coefficient for maintenance practices (-0.020) highlights important complexities in maintenance management that previous studies have not adequately addressed. While Cunningham and Miller (2020) advocated for increased maintenance frequency, the current findings suggest that this relationship is more nuanced. The negative coefficient indicates that reactive maintenance approaches may be less effective than proactive strategies, emphasising the need for systematic prevention rather than problem-response cycles.

This finding contrasts with conventional assumptions that more maintenance automatically leads to better performance. Instead, it suggests that maintenance frequency serves as an indicator of underlying infrastructure problems rather than evidence of effective management. This interpretation aligns with Montgomery et al. (2021), who cautioned that inappropriate interventions can potentially cause damage rather than improvement. The implication is that maintenance quality and appropriateness matter more than frequency alone.

Article DOI: https://doi.org/10.37284/eaje.8.2.3995

Practical Implications for Infrastructure Management

Model validation results spanning the complete performance spectrum demonstrate practical applicability for culvert assessment and maintenance prioritisation. The clear performance categorisation enables stakeholders to identify intervention urgency and allocate resources efficiently based on quantitative assessment rather than subjective evaluation alone. This represents a significant advancement over current practices in Kinondoni District, where Edward (2022) documented predominantly reactive approaches lacking systematic assessment protocols.

The validated regression model offers reliable performance prediction capabilities, enabling proactive maintenance planning and systematic intervention targeting. This addresses the critical gap identified by Zhang et al. (2024), who noted that standardised assessment approaches remain underdeveloped in developing country contexts. By providing quantitative tools accessible to practitioners with varying technical capacities, this study facilitates evidence-based infrastructure management in resource-constrained environments.

CONCLUSION

This research successfully developed a comprehensive maintenance management model that significantly enhances culvert performance assessment and maintenance planning in Kinondoni District Council. The study identified and prioritised seven critical factors affecting culvert performance, with structural integrity and hydraulic capacity emerging as paramount concerns. The developed multiple regression model demonstrated strong predictive capability ($R = 0.780$, $R^2 = 0.608$, $p < 0.001$), explaining approximately 61% of the variance in culvert performance and providing quantitative tools for evidence-based decision-making.

Key findings demonstrate that systematic, evidence-based maintenance management can significantly improve infrastructure performance while optimising resource utilisation efficiency. Climate change adaptation emerged as the most influential positive factor, emphasising the critical importance of future-proofing drainage infrastructure against changing precipitation patterns. Field validation across culverts ranging from good to poor condition confirmed the model's practical applicability and discriminatory capability.

The clear factor hierarchy provides evidence-based guidance for maintenance prioritisation, while the validated regression model enables proactive maintenance planning and systematic intervention targeting. The model's ability to generate quantitative performance scores facilitates categorisation into distinct condition levels that align with practical maintenance management needs, addressing critical gaps in current practice where reactive approaches predominate.

This study contributes to infrastructure management knowledge by developing and validating a context-specific maintenance model tailored to developing urban environments. The research demonstrates that quantitative modelling approaches can be successfully implemented in resource-constrained settings, providing practical tools that enhance infrastructure resilience and sustainability.

RECOMMENDATIONS

Based on comprehensive research findings, the following recommendations are proposed:

Implementation of Systematic Performance Assessment Protocols

The validated regression model should be integrated into routine infrastructure management practices as the primary tool for culvert condition assessment. Training programs should be developed for technical staff on model application, data collection

Article DOI: https://doi.org/10.37284/eaje.8.2.3995

requirements, and performance score interpretation. Regular assessment cycles should be established to monitor performance trends and identify deteriorating conditions before critical failures occur.

Prioritisation of Structural Integrity and Hydraulic Capacity Interventions

Given the paramount importance of structural integrity (84.3% RII) and hydraulic capacity (83.4% RII), immediate resources should be allocated to assess and enhance these critical aspects. Structural reinforcement programs should target culverts showing signs of deterioration, while hydraulic improvements should focus on capacity expansion and flow optimisation.

Development of Proactive Maintenance Strategies

The negative coefficient for maintenance practices indicates the need to shift from reactive to proactive approaches. Preventive maintenance schedules should be established based on performance predictions rather than failure occurrences. Regular cleaning and debris removal programs should be implemented to address desilting and blockage issues before they compromise performance.

Enhancement of Climate Change Adaptation Measures

The highest positive coefficient for climate change adaptation emphasises the critical importance of future-proofing infrastructure. Culvert capacity should be evaluated against projected precipitation increases, and adaptation measures should be implemented to handle more intense rainfall events. Design standards should be updated to reflect changing environmental conditions.

Establishment of Performance-Based Resource Allocation

A formal classification system should be implemented based on model performance categories: major rehabilitation for scores below 25%, scheduled repair for 25-45%, routine maintenance for 45-65%, and monitoring for scores above 65%. Budget allocation should reflect these evidence-based priorities.

Creation of Digital Management Systems

Comprehensive databases should be developed to store culvert inventory data, condition assessments, maintenance records, and performance predictions. Mobile applications should facilitate field data collection and real-time updates. Geographic Information Systems integration should enable spatial analysis and optimise maintenance routing.

Development of Local Technical Capacity

Training programs should be established for maintenance personnel, focusing on systematic assessment techniques, appropriate intervention methods, and performance monitoring. Regular workshops should update personnel on best practices and emerging technologies.

REFERENCES

Aramburu Paucar, J. M., Martinez-Capel, F., Puig-Mengual, C. A., Muñoz-Mas, R., Betagnoli, A., & Tonina, D. (2024). Flood flows as a natural tool of river restoration. Available at SSRN 4563705.

Cunningham, P. R., & Miller, S. A. (2020). Quantitative assessment of alkali-activated materials: Environmental impact and property assessments. *Journal of Infrastructure Systems*, *26*(3), 04020021.

Edward, M. (2022). Assessment of urban drainage infrastructure performance in Dar es Salaam. *Tanzanian Journal of Engineering and Technology*, *41*(2), 45-58.

Meegoda, J. N., & Zou, J. (2015). Sustainable infrastructure management using multiple regression analysis. *Journal of Infrastructure Systems*, *21*(3), 04014045.

Article DOI: https://doi.org/10.37284/eaje.8.2.3995

Montgomery, D. C., Peck, E. A., & Vining, G. G. (2021). *Introduction to linear regression analysis* (6th ed.). John Wiley & Sons.

Schoeman, C. (2019). Infrastructure asset management in developing countries: Challenges and opportunities. *Infrastructure Asset Management*, *6*(4), 234-245.

Wang, W., Zaheer, Q., Qiu, S., Wang, W., Ai, C., Wang, J., Wang, S., & Hu, W. (2023). Transportation infrastructure management. In *Digital twin technologies in transportation infrastructure management* (pp. 75-109). Springer.

Wysokowski, A. (2019). Factors affecting culvert performance and maintenance requirements. *Engineering Structures*, *195*, 285-295.

Zhang, Y., Wang, E., & Gong, Y. (2024). A structural optimization of urban drainage systems: An optimization approach for mitigating urban floods. *Water*, *16*(12), 1696.

Zou, J. (2015). Culvert maintenance and rehabilitation strategies for sustainable infrastructure management. *Transportation Research Record*, *2522*(1), 98-107.

