

Original Article

Optimization of Culvert Dimensions Using HEC-RAS on River Mutha: A Hydro-Environmental Approach

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Abstract - This study examines the effects on hydraulics and the environment of installing zigzag culverts spaced 500 meters apart along a modified river channel. Optimizing culvert dimensions to improve water quality and efficiently regulate flow is the main goal. Hydraulic performance and flow behavior are assessed using a combination of HEC-RAS simulations and physical modeling with a distorted Froude scale (built in ferrocrete). The best culvert size, according to simulation results, is 15.5 m × 1.0 m. This size successfully eliminates overtopping threats by providing the lowest upstream water surface height (1.8 m) and a positive freeboard of 0.2 m. The physical model's experimental results validated the numerical results by confirming a 37.25% (prototype) and 38.09% (model) decrease in Velocity. Monitoring of the water quality before and after the installation of the Culvert showed notable improvements: the pH rose by 6.79 %, the dissolved oxygen improved by 64.68 %, and the Total suspended particles reduced by 79.63%. These findings demonstrate that the suggested culvert design improves environmental conditions by reducing silt, increasing aeration, and increasing hydraulic efficiency. A sustainable method for managing river flow and enhancing water quality is shown by the integrated modeling technique.

Keywords - Culverts optimization, Dimensional analysis, HEC RAS, Physical model, Water quality monitoring.

1. Introduction

Since ancient times, culverts have been crucial hydraulic devices for transit over streams, bridge highways, and waterways (Kağan CEBE et al., 2024). Challenges arise from the unpredictable seasonal flow and the urbanization of river systems, like the Mutha River in Pune, India. This work aims to use distorted Froude modeling techniques to develop a reliable culvert for such riverine circumstances. According to H. Methods et al. (2003), the Culvert's modest cross-section can raise upstream water surface elevations by several meters, resulting in greater upstream flood levels than they would be without the Culvert and the embankment.

A culvert's flow behavior is primarily determined by its dimensions, shape, channel Manning coefficient, etc. (Dwi Rian Sulaeman 2023). Headwater depth has a major impact on culvert hydraulic design. Upstream flooding may result from the embankment overtopping or from the flow backing up if the headwater level is insufficient to permit flow through the Culvert (Tawfiq Salma 2012). A suitable culvert dimension and number must be established before installation to ensure the anticipated water flow (Edwards, 2011). Numerous engineering and non-engineering aspects are taken into account throughout the culvert design process, including the Culvert's size and shape, hydraulics, placement, etc (Normann et al. 2001). Water quality can be

negatively impacted by culverts that are too small or incorrectly positioned (Ola Adel Qasim 2018). The most common cross-sectional shapes for culverts are box, circular, elliptical, pipe-arch, etc (Normann et al. 2001). Culvert shape is determined by a number of parameters, including construction cost, headwater elevation constraints, hydraulic performance, etc (Mahmood, 2004). A box culvert can provide a hydraulically adequate design that can accommodate a large flow compared to other cross-sections. Hydraulic capacity with low headwater can be satisfied by increasing span dimensions. A variety of materials are used to build culverts. Every substance has unique qualities, benefits, and drawbacks. When building culverts, concrete, Corrugated Metal Pipe (CMP), and smooth steel are the three materials most frequently utilized (Tawfiq Salma 2012).

Kağan CEBE et. al. (2024) suggested that HEC-RAS is capable of simulating a large number of hydraulic characteristics of a real stream and more correctly depicts the flows that occur on the channel at the Culvert's inlet and outlet as well as at downstream. The Saint-Venant hydraulic equations form the basis of the HEC-RAS program, which makes it easier to estimate the size of floodplains, calculate water surface heights, and distribute flood velocities. Applying mathematical models is crucial and advantageous in these hydrological simulations (G. Dorin et al. 2022). It



may be stated that HEC-RAS shows a high degree of accuracy in forecasting water levels and areas impacted by flooding during extreme hydrological events, even with relatively minimal input data (N. N. Zainal, S. H. A. Talib, 2024). During periods of significant floods, HEC-RAS is a helpful tool for creating safety and management. For environmental and urbanization reasons, it is essential to comprehend the flow behavior of meandering rivers in order to build water structures, lessen erosion, and avoid flooding (Cem Yilmazer H and Güner 2024). Wang used the HEC-RAS model in his study to analyze the water surface profile of an existing project.

(C. H. Wang 2014). Olaniyan O.S.et. al. (2014) used HEC RAS to simulate the flow of water through natural channels, such as rivers, used to modify the existing culvert channels. Tian Wu et al. Al. suggested that HEC-RAS is an extremely useful and powerful program for calculating water profiles. HEC-RAS has been used in a number of studies, including flood analysis, hydrologic simulation, discharge estimation, backwater height calculation, sediment transport simulation, river water surface profile simulation, etc (Mohd Talha Anees et.al. 2015). These studies suggest using distorted Froude modeling, especially when paired with software like HEC-RAS, to produce hydraulically efficient and environmentally benign culvert designs. Hydraulic modeling for culverts has traditionally relied on dimensional analysis and physical similarities (Hubert Chanson 1999). In order to optimize the structure's design, guarantee its safe functioning, and/or speed up the decision-making process, engineers employ physical hydraulic modeling (Hubert Chanson 1999). In real-world engineering, the equations are either unknown or too complex to solve; frequently, the only way to get accurate information is through experimentation.

In order to save time and money, most tests are carried out on a geometrically scaled model rather than the full-size Prototype; in these cases, it is crucial to scale the results correctly. Here, we present a potent technique called dimensional analysis. The three requirements that a model and a prototype must meet to be completely similar are geometric, kinematic, and dynamic similarity. The Froude number ratio in Froude-scaled models must be met, i.e., one, when converting model measurements to prototype quantities (NICHOLAS P. WALLERSTEIN et.al. 2001).

According to Normann et al. (2001), culverts are essential hydraulic structures that preserve channel stability, sediment transport, and flood channeling. Conventional designs frequently ignore environmental effects like silt accumulation and deterioration of water quality in favor of hydraulic efficiency. Accurate simulations of water surface profiles, backwater conditions, and culvert hydraulics are now possible thanks to the advent of modeling tools like HEC-RAS (Wang, 2014; USACE, 2023; Zainal & Talib, 2024). Culvert geometry has a significant impact on flow

velocity, deposition, and scour patterns, according to studies on flow and sediment dynamics close to culverts (Dorin et al., 2022; Wallerstein et al., 2001; Rowley & Hotchkiss, 2014). Eco-hydraulic characteristics are the focus of a recent study that goes beyond hydraulics. (Yilmazer & Güner, 2024; Olaniyan et al., 2014; Xue et al., 2021) Research shows that culvert design and channel change affect biofilm formation, dissolved oxygen dynamics, and pollution transfer. Although there are assessments of the water quality of contaminated rivers (Jagtap & Manivanan, 2019; Fadtare & Mane, 2007), they frequently do not incorporate structural or hydraulic remedies. This highlights a research gap where culvert optimization is rarely assessed for both water quality improvement and hydraulic conveyance improvement. In order to evaluate culvert designs that provide effective flow management and environmental improvement, the current work combines HEC-RAS modeling with experimental monitoring.

1.1. Problem Statement

Water quality downstream may deteriorate due to conventional culvert design, which may guarantee discharge transportation but may also unintentionally cause water stagnation, silt buildup, or insufficient oxygen transfer. There is an urgent need to find culvert layouts that may concurrently address growing concerns about environmental sustainability and flood resistance.

- Maintain hydraulic efficiency by making sure there is enough discharge and preventing overtopping.
- Reduce pollution loads and raise DO levels to enhance the water quality.

1.2. Research Gap Identified

The majority of culvert studies that are now available concentrate primarily on hydraulic efficiency, flood management, and structural safety; their impact on water quality metrics (DO, BOD, TSS, COD, etc.) is usually disregarded. Only a small number of studies have combined physical experiments and HEC-RAS modeling to evaluate how culvert designs can maximize environmental quality and flow performance. Therefore, design strategies that connect culvert shape to long-term water quality enhancement are lacking.

2. Novelty of Work

This study presents a novel way to integrate hydraulic modeling using HEC-RAS with water quality assessment. It focuses on optimizing culvert dimensions as a tool for both environmental improvement and hydraulic safety. In contrast to earlier research that focuses on flood conveyance, this study:

1. Culvert geometry is directly linked to trends in pollution reduction (TSS) and the augmentation of DO.
2. Makes sure that the results are robust by verifying numerical predictions through physical model experimentation.

3. Suggests culvert dimensions that have the ability to regulate water quality in an eco-hydraulic manner, showcasing their potential as affordable, scalable solutions.

The research fills this gap by providing useful methods for sustainable channel management within a multidisciplinary framework that combines hydraulic simulation, environmental performance, and structural design. Suggests culvert dimensions that have the ability to regulate water quality in an eco-hydraulic manner, showcasing their potential as affordable, scalable solutions.

3. Objectives

- To optimize culvert dimensions using HEC-RAS simulations and distorted Froude modeling, ensuring efficient hydraulic performance under design flow conditions.
- To monitor the quality of water for dissolved oxygen, Total suspended solids, and pH on the physical model

4. Methodology Adopted

The proposed methodology follows a structured workflow shown in Figure 1. Numerical modeling, physical

experimentation, and optimization are all combined in this study's integrated technique. Extensive hydrological, topographical, and environmental data were first gathered to characterise the study site precisely. After that, a deformed physical model was created using Froude number similarity, and to accommodate real-world scaling limitations, geometric distortion was included.

An optimization system that took hydraulic restrictions and objective functions into account was developed to find the best culvert dimensions. Water surface profiles, flow patterns, and velocity distribution were among the flow parameters that were simulated using HEC-RAS to assess the optimum designs.

The hydraulic and environmental performance of the optimized design was then confirmed by a series of tests carried out on the built physical model, with an emphasis on flow behavior and aeration potential. After these tests, water quality monitoring was done in the physical model to measure changes in important parameters, such as turbidity, total solids, and dissolved oxygen. This allowed for an assessment of the environmental efficacy of the suggested culvert arrangement.

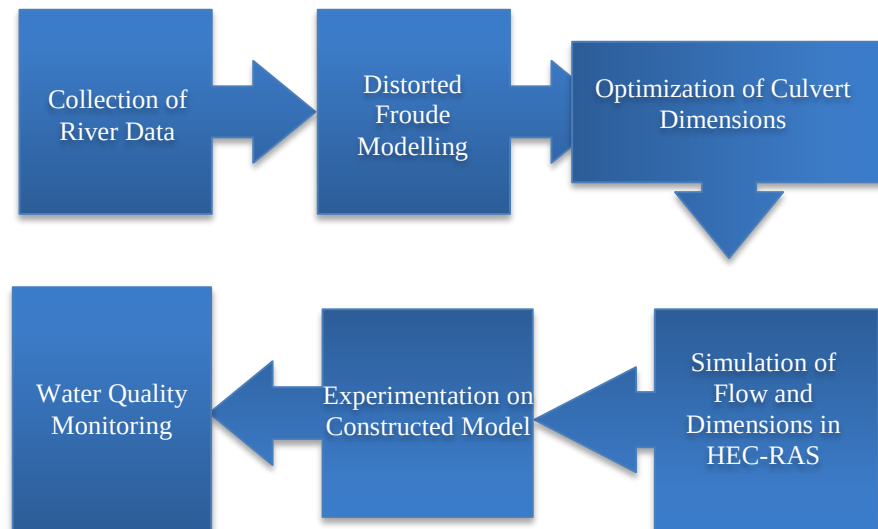


Fig. 1 Work flow for methodology

4.1. Collection of Data

The Mula, Mutha, and Pavana rivers flow through the center of Pune, which is located at 18°31' N and 73°51' E (Vinaya Fadtare and T.T. Mane 2007). Rivers are important for the growth of society as well as the economy (Shruti J. Dr. R Manivanan 2019). Monitoring water quality is crucial for determining contamination and evaluating environmental hazards (Muthulakshmi et al. 2013). Before installing any treatment system, the river's water quality must be accurately assessed, according to earlier research. Figure 2 shows 2km selected stretch on the River Mutha from Mhatre Bridge to

Omkareshwar Temple for the present study. A rectangular open channel that transports water discharge from upstream to downstream was the channel that was used in this investigation. The current open channel had a 2 m high levee on both sides, a base width of 30 m, and an average depth of 1.09 m. The length of the existing rectangular channel for study was 2000 m. Average velocity and average water depths were recorded using the current meter, which was 0.47 m/s and 1.09m, as shown in Figures 3 and 4, respectively. The discharge of the channel was recorded as 15.37 m³/s, measured by the area velocity method.

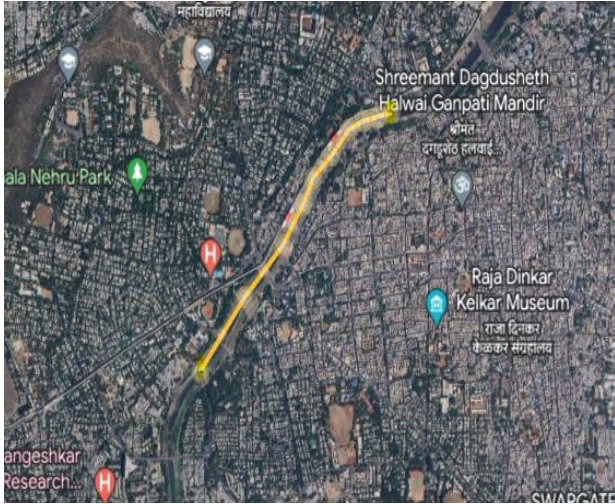


Fig. 2 Study area on river mutha (source: Google Earth)



Fig. 3 Measurement of velocity using current meter



Fig. 4 Measurement of water depths

4.2. Model Scaling

Dimensional Analysis is an economical technique or process that makes use of dimensions to solve a problem. The Froude scaling principle is used for the laboratory setting to create a distorted physical model for a real flow system. The Froude scaling principle involves maintaining an equal Froude number in the model and Prototype to achieve similarity in flow. X_r is selected as 200, Z_r is selected as 20, and the Distortion ratio is $X_r / Z_r = 10$. The distorted Froude model is designed for the collected River data shown in Table 1

Table 1. Distorted froude model calculations

Parameters with unit	Scale ratio with Froude law (distorted model)	River Dimensions (Prototype)	Distorted Froud model Dimensions	Scale Used
Length (m)	X_r	2000 m	10 m	$X_r = 1:200$
Width (m)	Z_r	30 m	0.15 m	$Z_r = 1:20$
Levee (m)	Z_r	2m	0.1 m	$Z_r = 1:20$
Depth of water	Z_r	1.09 m	0.0545m	$Z_r = 1:20$
Area of flow (m ²)	-	32.7 m ²	8.173x10 ⁻³ m ²	-
Velocity (m/s)	$(Z_r)^{1/2}$	0.47 m/s	0.1050 m/s	-
Discharge (m ³ /s)	$X_r Z_r^{3/2}$	15.37 m ³ /s	8.5921x10 ⁻⁴ m ³ /s	-
Time (s)	$X_r / (Z_r)^{1/2}$	65.06 min	1.46 min	-
Froude Number	-	0.45	0.449	-

4.3. Optimization of Culvert Dimension

To facilitate a controlled and modified flow regime within the river channel, a system of culvert installations was proposed at uniform intervals of 500 meters. The culverts are alternately oriented in a zigzag pattern, commencing with an outlet on the left bank at the downstream end and alternating to the right upstream. This staggered configuration induces a meandering flow path, significantly reducing flow velocity while enhancing aeration through increased turbulence and surface interaction. A physical modeling study was recommended to further analyze the hydraulic behavior resulting from this configuration. Computational simulations were conducted using the HEC-RAS hydraulic modeling software to evaluate flow characteristics and to determine the optimal culvert dimensions iteratively. According to Kazem et al., the initial design's permitted freeboard is one-sixth of the total depth under conditions of uniform flow. The prototype culvert dimensions were finalized based on trial iterations as 15.5 m $\times$ 1.0 m, with the corresponding geometrically scaled model dimensions determined as 0.0775 m $\times$ 0.05 m. An optimization analysis within HEC-RAS validated the efficacy of the selected configuration.

4.4. HEC-RAS Simulation

Hydrologic Engineering Centre-River Analysis System, or HEC-RAS, is a popular program created by the U.S. Army Corps of Engineers that focuses on rivers, open channel hydraulics, and culvert design skills. HEC RAS software is used to simulate the Prototype & Distorted Froude model with culvert design to establish the modified flow pattern in River Mutha. HEC-RAS sensitivity simulations were used in an optimization research to guarantee hydraulic efficiency.

Several culvert size combinations were evaluated for a given discharge for Prototype & model, such as changing the height from 0.7m to 1 m and the width from 10 m to 15.5 m., in order to avoid upstream flooding and reduce headwater elevation, which has to stay below the limits. In order to balance construction feasibility and hydraulic performance, the ideal culvert configuration was determined to be 15.5 m $\times$ 1 m (Prototype) & 0.0775 m $\times$ 0.05 m (Scaled Model). The following steps are to be followed for the study of Hydraulic Behaviour of the river for the Prototype and Model. Optimization study was carried out to select the dimensions of the Culvert in the Prototype as well as in the Model.

Step 1: Creation of a new HEC-RAS project

Step 2: Open the geometry editor window and create a new river and reach

River: Mutha River

Reach: Model

Step 3: Go into River Station. Next, input the geometric data, which includes elevation and station data.

Upon summing up all the data, the HEC-RAS program produces a geometric cross-section. The river's bed material can be used to determine the value of "n."

Step 4: After entering the geometric data, the profile plot can be seen in Figure 5

Step 5: Design a Deck to provide a culvert shown in Figure 6

Step 6: After creating a deck design, indicate the position, size, and orientation of the Culvert within the river system. Describe the characteristics of the Culvert, such as its dimensions, type, shape, etc., as shown in the Figure. 7

Step 7: Run the HEC-RAS simulation to model the hydraulic behaviour of the river system, including the Culvert.

Step 8: Refer to Figure 8 to examine the simulation results, taking note of the Culvert's discharge capacity, flow velocities, and water surface profiles in the Output Table.

Step 9: Repeat the above steps for Prototype to get the results for Prototype, including Water Surface Profile, flow velocities, and discharge capacities of the Culvert in the Output Table.

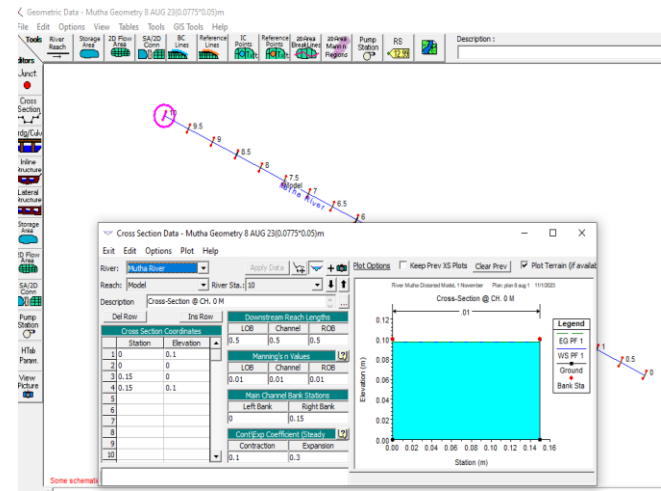


Fig. 5 Geometry of the distorted model

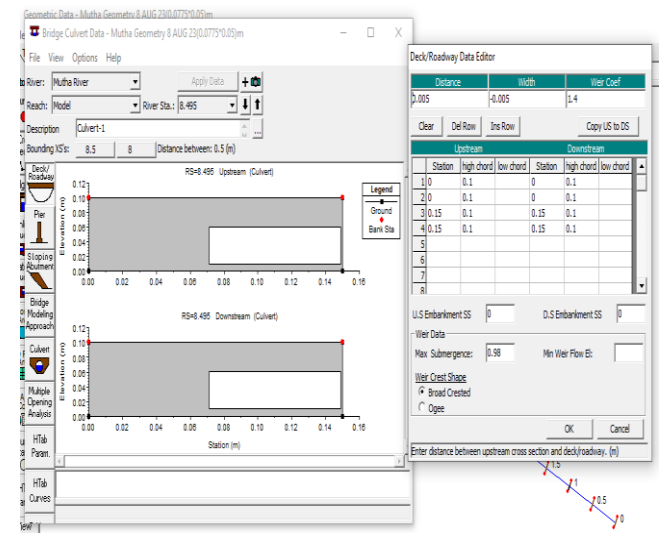


Fig. 6 Deck design in HEC RAS for distorted model

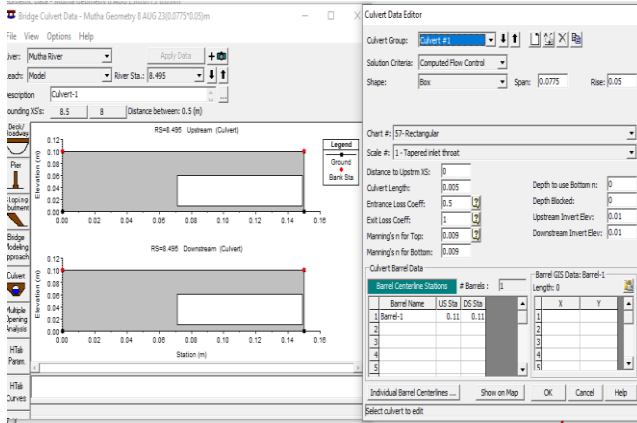


Fig. 7 Culvert design in HEC RAS for distorted model

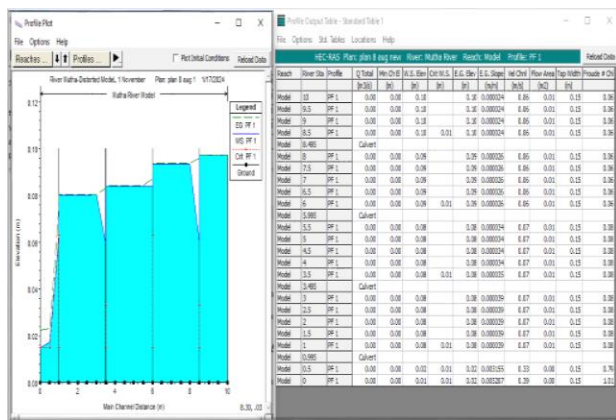


Fig. 8 Water surface profile & output table for distorted model

4.5. Experimentation on a Physical Model

The hydraulic behavior of the river system was replicated, and the effectiveness of culvert projects was evaluated through physical model testing using a distorted Froude-scaled model. The dynamic similarity between the model and the Prototype was ensured by maintaining the Froude number (Fr), which controls the similarity of free-surface flows. Different scaling ratios for horizontal and vertical dimensions were used to generate geometric distortion in order to increase measurement accuracy and fit site constraints, especially in areas with shallow flow (Chanson, 2004). The parameter can also be safely converted between different systems of units by expressing it in physical dimensions. The idea that the model and Prototype are similar forms the basis of research on physical models. This theory offers recommendations for experiment setup, model parameter calculation, result processing, validity limits, and potential scale effects (Novak et al., 2010). In order to represent channel geometry with excellent structural integrity, ferrocrete (ferrocement concrete) was used to create the physical model, which can be seen in Figure 9.

This material was long-lasting, waterproof, and formable. Various model runs were performed on the physical model kept in the Fluid Mechanics Laboratory in

SCOE, Pune. Under various trial runs, flow conditions and water elevations were measured. The culvert configurations were tested for their capacity to lower flow velocity and encourage aeration. The findings were applied to improve design parameters for field use and validate numerical simulations. Distorted models are especially helpful for shallow flows and complex geometries, where vertical exaggeration improves the accuracy of physical observations (Heller, 2011).



Fig. 9 Physical model of ferrocrete

4.6. Water Quality Monitoring

In order to develop and manage water resources rationally, one of the first measures needed is water quality monitoring (CPCB 2007-08). To indicate, regulate, or forecast changes or trends in a specific water body's quality, a well-designed and well-managed water quality monitoring system is necessary.

This allows for the implementation of corrective or preventive actions to restore and preserve the ecological balance of the water body. Monitoring will ensure water quality parameters such as dissolved oxygen and suspended solids remain within permissible limits.

Physical modeling was used to assess the changes in water quality brought about by installing staggered culverts in 30 samples, emphasising pH, Total Suspended Solids (TSS), and Dissolved Oxygen (DO). As prescribed by APHA (2017), water quality assessment using standard methods was carried out in the Environmental Research laboratory in Sinhgad College of Engineering, Pune- 41, for Inlet and Outlet (with Culverts) before and after experimentation, as shown in the Figure. 10 below.

Figure 11 shows a Comparison of Dissolved oxygen (mg/l) before and after experimentation, i.e., at Inlet & Outlet (with Culverts). Figures 12 and 13 show a Comparison of Total Suspended Solids (mg/l) and a Comparison of pH before and after experimentation, i.e., at the Inlet and Outlet (with Culverts), respectively.



Fig. 10 Inlet and Outlet (with Culverts) sample

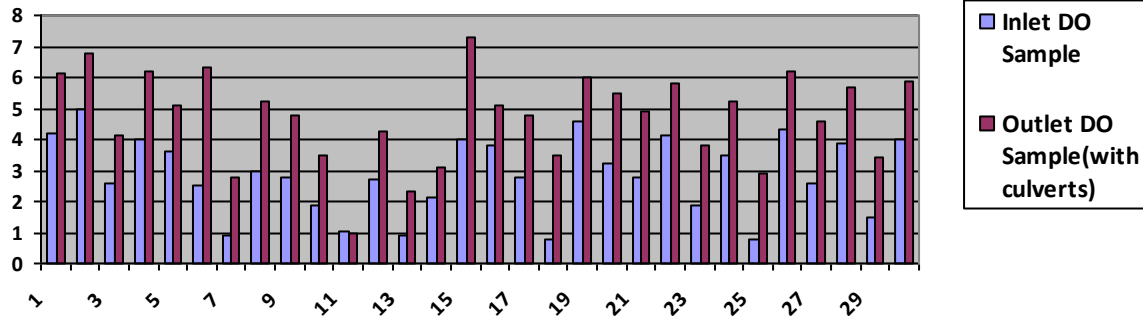


Fig. 11 Comparison of dissolved oxygen (mg/l) at Inlet & Outlet (with Culverts)

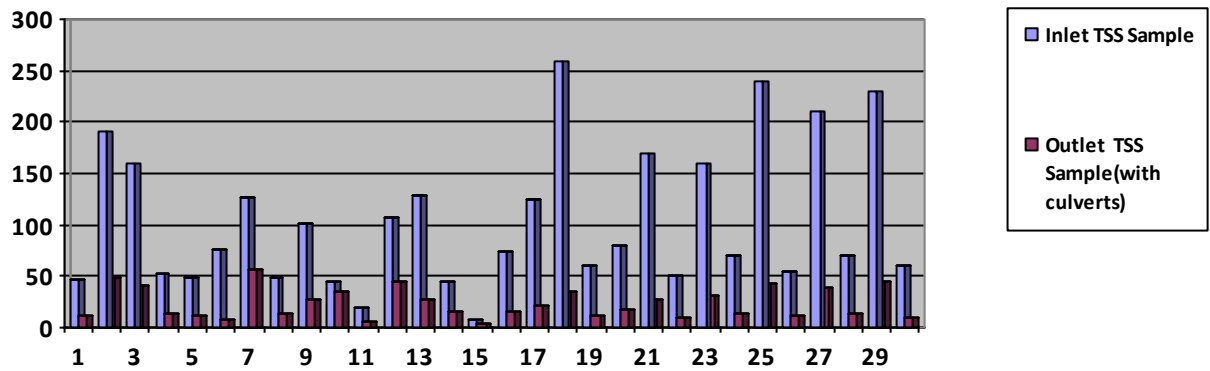


Fig. 12 Comparison of total suspended solids (mg/l) at Inlet & Outlet (with Culverts)

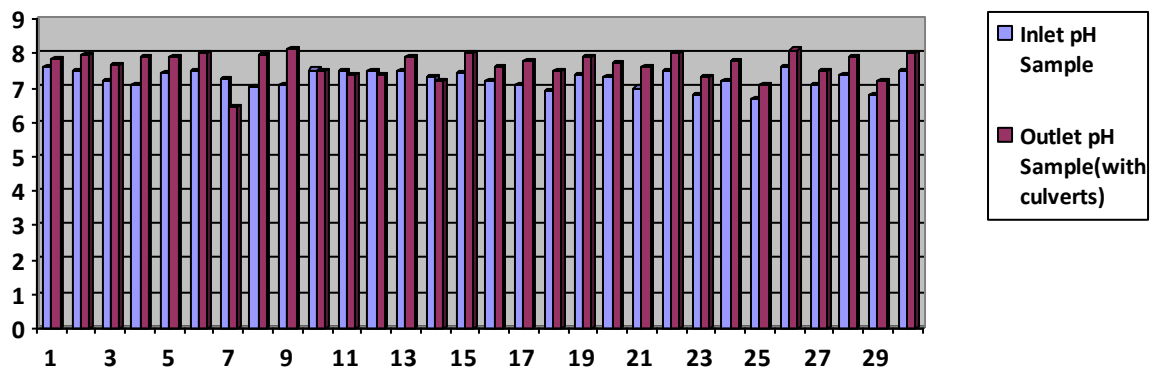


Fig. 13 Comparison of pH at inlet & outlet (with Culverts)

Table 2. Simulations using HEC RAS for optimize culvert dimensions

Simulation Number	Size of Culvert in Prototype	Percentage Opening	Water Surface Elevation in Upstream(m)	Freeboard (m)	Overtopping of Water
1	10m * 0.7 m	11.66 %	2.36	-0.36	Yes
2	13m * 0.8 m	17.33 %	2.15	-0.15	Yes
3	14m * 0.8 m	18.66%	2.08	-0.08	Yes
4	14m * 0.9m	21%	2	0	No
5	14 m * 1m	23.33%	1.9	0.1	No
6	15.5 m* 1m	25.83%	1.8	0.2	No

5. Results and Discussion

The hydraulic efficiency and impact on water quality of installing culverts in a staggered zigzag pattern were assessed using physical and numerical modeling techniques. To find the ideal culvert size for controlling upstream water surface elevation under design flow circumstances, a set of six HEC-RAS simulations was run, which can be seen in Table 2.

We looked at culverts with sizes between 10 m × 0.7 m and 15.5 m × 1.0 m. According to the findings, there is a direct correlation between the size of the culvert aperture and the elevation of the upstream water. Freeboard was negative in simulations 1 through 3 (openings ≤ 18.66%), indicating overtopping of water and insufficient flow capacity. When a 14 m × 0.9 m culvert was used in Simulation 4, the freeboard was zero, indicating the boundary between safe and unsafe flow conditions. With positive freeboard values of 0.1 and 0.2 meters, respectively, in simulations 5 and 6, overtopping was prevented, and hydraulic performance was stable. Iterative HEC-RAS simulations were used to

Estimate the optimal culvert dimensions, which were ultimately determined to be 15.5 m × 1.0 m for the Prototype, i.e., simulation 6 and 0.0775 m × 0.05 m for the scaled physical model made using distorted Froude scaling. The results of the HEC-RAS simulation showed that the zigzag culvert configuration significantly reduced flow velocity. Average Velocity was reduced by 37.25% in the Prototype and 38.09% in the distorted model when compared to the unaltered channel flow. The fidelity with which the distorted model captured the hydraulic behavior of the prototype system was confirmed by this alignment in the results. The simulation results were validated by ferrocrete model experiments. A more consistent velocity distribution throughout the channel cross-section was achieved by the controlled redirection of flow channels caused by the employment of various opening orientations. Increased turbulence at alternate culvert outputs clearly improved surface aeration. After the experiment, monitoring the water quality revealed increases in Dissolved Oxygen (DO) levels near the culvert exits, which were ascribed to improved aeration and mixing. The majority of the samples showed a notable rise in DO, suggesting that the zigzag culvert shape improved aeration. The average DO improved by almost

64.68 %, rising from 2.86 mg/L (inlet) to 4.71 mg/L (outlet). Due to reduced velocities and localized energy dissipation close to culvert exits, this trend indicates successful sediment deposition. There was a continuous and significant decrease in the TSS values.

From 115.03 mg/L (inlet) to 23.43 mg/L (outlet), the average TSS dropped by an average of almost 79.63%. Most samples showed a small increase in pH, suggesting a move toward more neutral or slightly alkaline circumstances. The average pH rose from 7.21 at the inlet to 7.70 at the outlet. This is explained by higher DO levels and less carbonic acid production, which is in line with research in aerated flow systems, which supports aquatic health. The summary of the percentage changes in water quality parameters at Inlet & Outlet can be seen in Table 3 across the 30 samples.

The current work shows that, when culvert dimensions are optimized using HEC-RAS modeling in conjunction with physical model experimentation, water quality parameters at the culvert outlet significantly improve when compared to input circumstances. For example, dissolved oxygen (DO) increased by 64.68%, and TSS consistently decreased by 79.63% in different trials. These gains are much greater than those documented in previous research, which mostly focused on sediment transport dynamics or hydraulic efficiency and infrequently connected culvert geometry to improved water quality. Our research incorporates environmental considerations directly into culvert design optimization, in contrast to traditional culvert design studies, like Xue et al. (2021), which focused primarily on microbial dynamics and examined the effects of culvert length and flow rate on biofilm formation and water quality, or Rowley & Hotchkiss (2014), which reported increased turbidity and pollutant loading due to sediment scour. By combining HEC-RAS modeling with physical testing and water quality evaluation, we ensure that culverts serve as natural treatment systems that enhance downstream water quality by encouraging aeration and sediment settling and serving as conveyance structures. Three important aspects are responsible for the improved outcomes:

- Culvert-Induced Aeration: Compared to conventional straight-flow systems, DO was greatly enhanced by

optimised culvert shape's turbulence and surface re-aeration zones.

- Improved Sediment Settling: TSS and BOD levels were lowered by the efficient settlement of suspended particles and organic matter due to a decrease in flow velocity and turbulence at an optimal size.
- Combining Modeling and Experimentation: This work integrated HEC-RAS simulations with physical validation, ensuring robust and dependable results,

whereas previous research used numerical models or field data.

Therefore, by introducing a novel design paradigm where culverts are thought of as hydraulic conveyance structures and environmental management instruments contributing to sustained water quality improvement, our methodology surpasses state-of-the-art methodologies.

Table 3. Summary of percentage changes at Inlet & Outlet

Parameter	Inlet Avg.	Outlet Avg.	% Change	Interpretation
Dissolved Oxygen(DO)	2.86 mg/L	4.71 mg/L	+64.68%	Significant improvement in aeration
Total Suspended Solids (TSS)	115.03 mg/L	23.43 mg/L	-79.63 %	Strong reduction in sediment load
pH	7.21	7.70	+6.796 %	Mild alkalinity increase, stabilizing

6. Conclusion

The findings of the HEC-RAS simulation demonstrated that by reducing upstream water surface heights and avoiding overtopping, culvert dimensions greatly increase hydraulic efficiency. The most efficient culvert size was determined to be 15.5 m × 1.0 m, which provided a safety buffer in terms of freeboard, stable flow behavior, and adequate discharge capacity. It is anticipated that this configuration, which was chosen for both numerical and physical modeling, will improve system resilience under fluctuating flow conditions, improve flow control, and lower the risk of flooding. The efficacy of the suggested culvert design is confirmed by the combined effects of sediment settling, turbulence-induced mixing, and velocity reduction. The concurrent trends in TSS reduction and DO improvement provide additional evidence

of the positive environmental effects of the changed flow path. The credibility of the model-prototype scaling and physical experimentation utilizing the ferrocrete-based distorted Froude model is reinforced by these results, which show good agreement with the numerical predictions derived from HEC-RAS simulations.

Author Contribution Statement

All authors influenced the study's conception and design. Data collection, analysis, and material preparation were carried out by RM and SS. RM wrote the original draft of the manuscript, and all writers provided feedback on earlier iterations. RM & SS have read and approved the finished product.

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Appendix 1

Output Table (Prototype)							Output Table (Distorted Model)							
Reach	River Station	Q Total	Velocity (m/s)	Velocity (m/s)	Percentage Reduction in velocity	Average Reduction in velocity	Reach	River Station	Q Total	Velocity (m/s)	Velocity (m/s)	Percentage Reduction in velocity	Average Reduction in velocity	
		(m3/s)	Before culverts	After culverts					(m3/s)	Before culverts	After culverts			
1	2000	15.37	0.47	0.27	42.55%	37.25%	Model	10	8.59* 10^-4	0.105	0.06	42.85%	38.09%	
1	1900	15.37					Model	9.5	8.59* 10^-4					
1	1800	15.37					Model	9	8.59* 10^-4					
1	1700	15.37					Model	8.5	8.59* 10^-4					
1	1699	Culvert					Model	8.495	Culvert					
1	1600	15.37	0.47	0.29	38.29%		Model	8	8.59* 10^-4	0.105	0.06	42.85%		
1	1500	15.37					Model	7.5	8.59* 10^-4					
1	1400	15.37					Model	7	8.59* 10^-4					
1	1300	15.37					Model	6.5	8.59* 10^-4					
1	1200	15.37					Model	6	8.59* 10^-4					
1	1199	Culvert					Model	5.995	Culvert					
1	1100	15.37	0.47	0.3	36.17%		Model	5.5	8.59* 10^-4	0.105	0.07	33.33%		
1	1000	15.37					Model	5	8.59* 10^-4					
1	900	15.37					Model	4.5	8.59* 10^-4					
1	800	15.37					Model	4	8.59* 10^-4					
1	700	15.37					Model	3.5	8.59* 10^-4					
1	699	Culvert					Model	3.495	Culvert					
1	600	15.37	0.47	0.32	32%		Model	3	8.59* 10^-4	0.105	0.07	33.33%		
1	500	15.37					Model	2.5	8.59* 10^-4					
1	400	15.37					Model	2	8.59* 10^-4					
1	300	15.37					Model	1.5	8.59* 10^-4					
1	200	15.37					Model	1	8.59* 10^-4					
1	199	Culvert					Model	0.995	Culvert					
1	100	15.37					Model	0.5	8.59* 10^-4					
1	0	15.37					Model	0	8.59* 10^-4					