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Design of Concrete Box Culvert Based on the Hydromorphometric Properties of Natural Drainage Basins: A Case Study of the Mesos-Suluq Road Culvert

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تصميم عبارة خرسانية صندوقية استنادا على الخصائص الهيدرومورفومترية لأحواض التصريف الطبيعية: عبارة طريق سلوق-مسوس، كحالة دراسية

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Abstract:
This study presents an integrated hydraulic and structural design approach for a concrete box culvert, addressing the intersection of the Messous-Suluq road with WadiBab basin. A comprehensive hydrological investigation of WadiBab basin, established by SCS-Type II method. Key parameters such as peak flow, time of concentration, and flood duration were estimated, deriving essential hydraulic requirements. A statistical rainfall analysis of historical data (1981-2022) was performed, defining design storm events and calculating a maximum discharge of 5.6 m³/sec for a 1000-year return period. The basin's concentration time was determined to be 25.4 hr, with runoff velocities 0.981 m/sec due to steep upstream slopes. Subsequently, a three-cell square box culvert was designed with dimensions of 3.5m in width and height, ensuring hydraulic efficiency. The structural design stand by AASHTO 3.4.1-2 LRFD specifications. All applicable loads, including self-weight, soil overload, live loads, were quantified. Structural analysis, performed with ROBOT2023 software, determined a maximum moment of 102.37 kN.m and a maximum shear force of 176.7 kN. Reinforcement detailing was executed, ensuring adequate resistance to these forces. The findings highlight that a morphohydrological analysis of WadiBab basin, employing ArcGIS 10.8 for geospatial data processing, provided the foundational data for this design. It was concluded that an optimally designed square box culvert can achieve equivalent structural and hydraulic stability. Recommendations include the integration of remote sensing and GIS for basin studies, the construction of dams for rainwater harvesting, regular culvert maintenance, and strategic placement of culverts within main valley courses to enhance flood management.

Keywords: Hydraulic and Structural Concrete Box Culvert Design, Basin Morphohydrological Analysis, WadiBab basin, Geospatial Analysis.

الملخص
تقدم هذه الدراسة منهجاً متكاملاً للتصميم الهيدروليكي والإنشائي لعبّارة صندوقية خرسانية، يتناول تحديداً تقاطع طريق المسوس-سلوق مع حوض وادي باب. تم إجراء تحقيق هيدرولوجي شامل لحوض وادي باب، وذلك بالاعتماد على طريقة SCS-Type II. وقد تم تقدير المعاملات الرئيسية مثل تدفق الذروة، وزمن التركيز, ومدة الفيضان، والتي استُخلصت منها المتطلبات الهيدروليكية الأساسية. أُجري تحليل إحصائي للأمطار بالاستناد إلى بيانات تاريخية (1981م-2022م)، حيث تم تحديد اقصى العواصف التصميمية وحساب أقصى تصريف يبلغ 5.6 m³/sec لفترة عودة مدتها 1000 عام. وقد حُدد زمن تركيز الحوض بـ 25.4ساعة، مع ملاحظة سرعات جريان سطحي تصل إلى 0.981m/sec بسبب الانحدارات الحادة في المنبع. تبع ذلك تصميم عبّارة صندوقية ثلاثية الخلايا ذات مقطع مربع، بأبعاد *3.5*متر عرضاً وارتفاعاً لكل خلية، مما يضمن الكفاءة الهيدروليكية. اعتمد التصميم الإنشائي على مواصفات AASHTO 3.4.*1-2*

LRFD. وتم تحديد وقياس جميع الأحمال المطبقة بدقة، بما في ذلك الوزن الذاتي للعبّارة، وحمل التربة الزائد والأحمال الحية ,أظهر التحليل الإنشائي، الذي أُجري باستخدام برنامج*R*OBOT2023، عزماً أقصى قدره 102.37 KN.*m*وقوة قص قصوى بلغت 176.7KN وتم حساب تفاصيل التسليح لضمان المقاومة الكافية لهذه القوى. تُسلط النتائج الضوء على أن التحليل المورفوهيدرولوجي لحوض وادي باب، باستخدام برنامج ArcGIS 10.8 لمعالجة البيانات الجغرافية المكانية، قد وفّر البيانات التأسيسية لهذا التصميم. وخُلصت الدراسة إلى أن العبّارة الصندوقية المربعة ذات التصميم الأمثل يمكن أن تحقق استقراراً إنشائياً وهيدروليكياً مكافئاً.

الكلمات المفتاحية: تصميم الهيدروليكي والإنشائي لعبّارة الصندوقية الخرسانية، التحليل المورفوهيدرولوجي للأحواض الطبيعية، حوض وادي باب، التحليل الجغرافي المكاني.

Introduction

Flood risk management and runoff control are crucial issues in civil and hydraulic engineering, especially in regions with distinct seasonal rainfall patterns and high-intensity precipitation. Floods are among the most destructive natural hazards, capable of causing extensive damage to infrastructure, disrupting road networks, and uncertain economic activities in a short period. Therefore, hydraulic structures that ensure the safe passage of water under roads are essential. Among these, concrete box culverts stand out as a prominent and widely used engineering solution. These culverts are not merely conduits for water; they are integral components of a comprehensive water resource management and flood control system. They are engineered to withstand the hydraulic pressures of flash floods while allowing traffic to continue uninterrupted. Their high drainage capacity, combined with exceptional durability and resistance to structural loads and harsh environmental conditions, makes them a superior choice. However, the success of these structures is not solely dependent on their structural design. It also requires a deep understanding of the hydrological and natural factors that govern runoff behavior.

Natural drainage basins are the primary source of water for culverts, and their morphometric and hydrological characteristics dictate the volume, intensity, and temporal distribution of water flow. Key factors such as basin size, shape, surface slope, drainage pattern, concentration time, and discharge intensity are critical in determining flood behavior and magnitude. A successful culvert design must therefore be based on a comprehensive analysis of these hydro-morphometric indicators as they are the most accurate tools for predicting flood characteristics. Neglecting these characteristics can lead to severe problems, including the culvert's inability to handle sudden discharges, which results in road flooding, erosion of the road embankment, or even complete structural failure. This is particularly critical in arid and semi-arid regions where rainfall is infrequent but often high-intensity and short-duration, significantly increasing the risk of flash floods. In such environments, morphometric analysis is an indispensable tool for designers, providing an accurate quantitative representation of the basin's nature and enabling a more realistic estimation of flood peaks than relying on rainfall data alone.

The relationship between the structural and hydraulic design of culverts and the hydro-morphometric characteristics of their drainage basins is fundamentally based on a precise understanding of how water flow within basin valleys interacts with the surrounding environment. This integrated approach ensures both environmental sustainability and the protection of infrastructure. It empowers engineers to determine the optimal dimensions, drainage capacity, and most suitable structural and hydraulic design techniques to efficiently discharge floodwater, thereby minimizing the risks of flooding and erosion.

In light of the above, this study aims to apply the principles of integrated structural and hydraulic design with the morphometric and hydrological characteristics of the Wadi Bab basin to design a culvert on the Saluq-Mesus road. This research will serve as a case study providing an in-depth analysis of the basin's morphometric and hydrological data, including its surface slope, drainage area, and water flow patterns.

Problem Statement

The WadiBab basin is a critical natural drainage area that directly impacts the Messous-Salouk road. Its specific hydromorphometric characteristics make it prone to generating sudden floods during periods of high-intensity rainfall. The basin's topography, which includes seasonal watercourses with varying gradients, facilitates a rapid concentration and acceleration of runoff towards the main wadi channel. This significantly increases the likelihood of high-magnitude flood events. While the region does not experience consistent rainfall, it is susceptible to short-duration, high-intensity storms, which elevate the risk of flash floods that could inundate the road and disrupt traffic. Previous flood events in adjacent basins have resulted in notable damage to local infrastructure, serving as a strong indication that WadiBab has the potential for similar destructive hydrological behavior under comparable meteorological conditions.

However, existing concrete box culverts in this region have often been designed using conventional methods that do not adequately incorporate the basin's comprehensive hydromorphometric properties.

This raises significant concerns regarding the capacity of these structures to accommodate potential peak discharges. Therefore, the problem this study addresses is the insufficient integration of the WadiBab basin's hydromorphometric characteristics into the design of culverts along the Messous-Salouk road. This deficiency may lead to an inability of the infrastructure to effectively manage sudden flood risks, particularly given the region's vulnerability to future flood events, as evidenced by recent occurrences in nearby wadis. This research aims to fill this critical knowledge and design gap by proposing an integrated approach.

Study Significance

The importance of this study lies in its aim to improve the resilience of vital road infrastructure against sudden flood hazards. It achieves this by developing and applying a methodology that directly integrates the hydromorphometric characteristics of the WadiBab basin into the hydraulic design of concrete box culverts. By analyzing key basin parameters, such as area, shape, slope, and stream density, this research enables a more precise estimation of extreme flood discharges, which is essential for creating a more realistic and robust design capable of withstanding severe hydrological conditions. This study holds significant practical value due to its direct application to the Messous-Salouk road, a critical transportation artery that supports regional economic and social development. Protecting this road from flood damage will ensure the continuity of transport services and reduce the likelihood of costly destruction and disruption.

Furthermore, this research provides a scientific model that can be replicated in other regions with similar climate and topographic conditions that are prone to sudden, high-intensity storms. The findings of this study therefore have broader implications for planning and designing hydraulic installations beyond the specific case study. This work also underscores the vital role of modern technologies, such as GIS and remote sensing, in extracting essential morphometric data from digital elevation models. The use of the USA Soil Conservation Service (SCS) model for estimating runoff is particularly relevant, as it provides a method for analyzing ungagged basins like WadiBab.

Study Objectives

The study aims to achieve a series of interconnected objectives to provide a systematic approach to the hydraulic and structural design of a box concrete culvert. This begins with a comprehensive hydrological investigation of the WadiBab basin, utilizing established hydrological modeling techniques to estimate key parameters such as peak flow, time of concentration, and flood duration, which are essential for determining the culvert's hydraulic requirements. Building on this, the research will perform a statistical rainfall analysis of historical data for the basin from 1981 to 2022.

The purpose of this is to determine the maximum rainfall quantities for various return periods, which will define the design storm event needed to calculate the maximum discharge the culvert must accommodate. Ultimately, the insights gained from both the hydrological and statistical analyses will be synthesized to develop an integrated hydraulic and structural design for the proposed concrete box culvert. This will include specifying optimal cross-sectional dimensions, analyzing all applicable design loads, and detailing the necessary concrete specifications and steel reinforcement to ensure the structure's long-term integrity and reliable performance.

The study area.

The WadiBab basin is located in the southwest of the Green Mountain in the State of Libya. Its main course extends southwest of the mountain, about 28 km away from the southeast of the city of Selouk and is about 50 km from the village of Mouss. The location of the basin is astronomically between latitudes($32^0 \quad 9' \quad 25''$,$29^0 \quad 35' \quad 20''$), and longitudes ($31^0 \quad 31' \quad 50''$, $20^0 \quad 51' \quad 18''$) (Figure 1) [1].

Previous studies

No prior studies have specifically addressed the structural and hydraulic design of culvert on the Messous-Suluq road based on the hydromorphometric characteristics of Wadi Bab basin. However, a significant body of research exists concerning the design of concrete box culverts, exploring various aspects of their performance and analysis.

Several researchers have investigated the structural behavior of culverts under different loading conditions. For instance, Roshan & Sagar (2019) conducted an analytical study on the impact of moving vehicle loads, examining various load cases and the influence of backfill material depth [2]. Similarly, Hasanain et al. (2022) focused on the structural design of square box culverts, analyzing the maximum moments and shear forces resulting from internal water and soil pressure [3]. Ali (2020) presented a study on the combined hydraulic and structural design of culverts, specifically addressing the distribution of live loads from traffic and their effect on the concrete culvert structure [4].

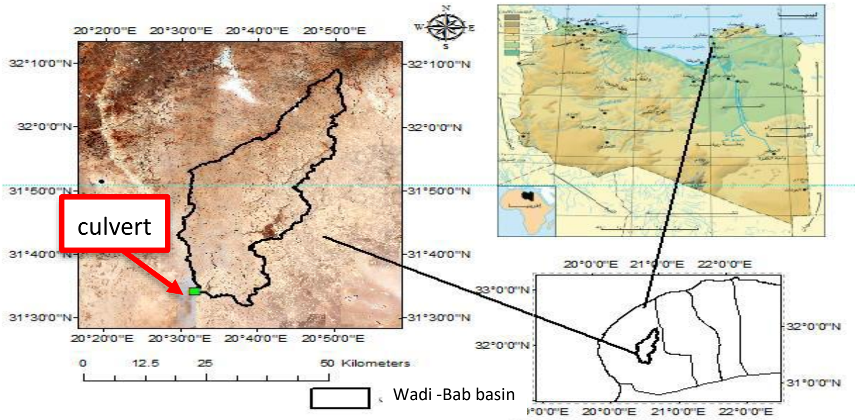

Figure 1: Location of WadiBab basin and the designed culvert.

Rao & Rao (2019) researched the design of culverts for high-traffic highways, encouraging for an integrated design methodology that considers both static and dynamic loads [5]. The application of advanced software for structural analysis has also been a prominent area of study. Al-Shammaa (2018) utilized STAAD.PRO for culvert analysis and compared the results to a full-width analysis to validate simplified methods [6]. In a similar vein, Krishna & Rajasekhar (2018) compared STAAD.Pro analysis results with manual calculations programmed in MATLAB and Excel, confirming a high degree of convergence and recommending multi-cell culverts for large spans to enhance efficiency [7].

Furthermore, Shrivastava & Pendharkar (2021) compared the structural performance of two- and three-cell culverts using STAAD.Pro, finding that multi-cell configurations significantly reduce internal forces, thereby improving overall structural performance [8]. Regarding hydrological and hydraulic considerations, Al-Omari et al. (2013) investigated the characteristics of drainage basins in Tikrit, Iraq, using established equations to determine design flow capacity [9]. More recently, Dawood & Mawlood (2024) addressed a specific flooding problem by designing a multi-cell culvert in Kurdistan, employing HEC-HMS and Bentley Culvert Master. Their study demonstrated that the new design was more efficient at accommodating large floods, which improved traffic safety and economic viability [10].

In summary, while prior research provides a strong foundation in culvert design and analysis across various structural and hydraulic aspects, there remains a notable gap in studies that specifically integrate the comprehensive hydromorphometric characteristics of Wadi Bab basin with the design of the Messous-Suluq road culvert. This current research aims to address and fill that specific gap

Study methodology and data used

This study is based on the descriptive approach to analyzing the topographic and spatial characteristics of WadiBab basin. This is done using spatial analysis tools within the GIS environment, as well as processing and analyzing satellite images. The statistical approach was also used to analyze rainfall data for the region. Employing the results obtained to complete the hydraulic and structural analysis of the phrase according to the following steps:

Statistical Analysis of Rainfall Data

Statistical analysis of rainfall data forms a key pillar in the design of flood phrases as it provides a scientific understanding of the behavior of historical rainfall data in a given area. This process begins with the collection of rain records and the application of applied statistics techniques to the rainfall data, with the aim of identifying the main characteristics of these data. Through iterative analysis, probabilistic distribution models can be used to estimate the probability of occurrence of extreme rain events and determine return periods, which is the expected duration of a storm recurrence of a given intensity. This information is vital in determining the design capacity of the facilities.

In addition, IDF analysis is an indispensable tool, linking the intensity, duration, and frequency of rainfall in IDF curves that guide engineers in the design of flood drainage facilities. Based on this statistical data, runoff volume is also estimated, ensuring that the design of the barges will be able to efficiently accommodate the expected water volumes. The value of the return period can be calculated using the Weibull method, where the following equation is used to calculate the return periods and the probability of a certain amount of rainfall [1]:

$$T = \frac{1}{P} \quad (1)$$

$$P = \frac{m}{n-1} \quad (2)$$

Where:

T= Return period years.

n=Number of years

m= rank of the intended quantity in the time series.
P= probability of repeating a specific return period.

Cadastral characteristics of drainage basins:

The digital hydrological analysis of the digital elevation model (DEM) is an advanced methodology in hydrology, aimed at studying and understanding the physical properties of natural drainage basins. This method is known for its ability to simulate water flow on the Earth's surface based on elevation data, making it easier to identify complex hydrological patterns. Digital elevation models (DEM) are a digital representation of the Earth's surface, where elevation data is stored for each cell (Pixel). These models provide the basis for a set of interrelated engineering processes that aim to:

1. **Fill:** This tool is used to fill depressions or small pits found in the (DEM). These depressions are errors in the data. The tool adjusts the elevation values of these cells to ensure continuous through the surface of the model.
2. **Flow Direction:** This tool creates a layer (Raster) that determines the direction of water flow from each cell to the neighboring cell with the steepest gradient.
3. **Flow Accumulation:** This tool is used to calculate the number of cells whose water flows to each cell in the model. Cells with high accumulation values indicate the presence of streams or streams, and the greater the value, the greater the amount of water flowing through that point, indicating a major watercourse.
4. **Watershed:** The tool requires determining the downstream point, which is the location at which the culvert will be designed. The tool uses the previously created “flow direction” layer to identify all the areas whose water flows to the specified downstream point, creating a polygon representing the entire boundary of a basin.

The cadastral and terrain characteristics of Wadi Bab basin under study were measured from the ArcGIS10.8 program, namely:

- Basin area (A km^2).
- Perimeter of the basin (P Km).
- Length of the main stream in the basin (L Km).
- Basin Width (W Km).
- Lowest natural ground level (H_{min} m).
- Highest natural ground level (H_{max} m).
- Average natural ground level (H_{avr} m)
- Slope in degree (S^0**)**

These operations are carried out using ArcGIS 10.8 software. Spatial Analyst tools in ArcGIS 10.8 allow engineers and researchers to convert spatial data into valuable hydrological information, contributing to an understanding of the flow dynamics of runoff.

Hydrological characteristics of drainage basins

With this study, a mathematical model was adopted to estimate runoff and flood flow depending on the terrain, climatic and morphometric characteristics of WadiBab basin, which is the model of USA soil conservation service (SCS), which is one of the most used models in estimating runoff basins that do not have hydrometric stations. The mathematical formulas are directly related to the calculation of the amount of runoff in WadiBab basin are presented in Table1.

Accurate estimation of flood runoff is a fundamental task in hydraulic engineering, especially when designing critical infrastructure such as concrete box culverts that require efficient water conveyance. The USA Soil Conservation Service (SCS) method, stands as one of the most effective and extensively utilized empirical tools for quantifying the volume and peak of surface runoff generated by specific rainfall events. This method's significance stems from its capability to reliably estimate runoff in natural drainage basins, even those lacking direct hydrological gauging stations, making it an invaluable asset for practical applications in ungagged regions.

Developed in the 1950s, the SCS method establishes a relationship between total rainfall, the physical characteristics of a drainage basin and the initial abstraction losses that occur before runoff commences. Moreover, it simplifies the development of a Synthetic Unit Hydrograph, enabling the estimation of both peak flow and the temporal distribution of runoff [11, 12]. The SCS method is therefore indispensable in the crucial initial phases of designing concrete box culverts: it provides the essential design peak flow needed to determine the culvert's hydraulic requirements, thus informing the hydraulic sizing to ensure optimal cell dimensions and number.

Additionally, it allows for the evaluation of culvert performance under various conditions and is particularly vital for providing hydrological data for ungagged basins, offering a practical solution where direct measurements are absent. In essence, the SCS method delivers a relatively straightforward methodology for estimating surface runoff, which forms the cornerstone of the hydraulic design for concrete box culverts, ultimately ensuring the development of sustainable and effective structures capable of protection infrastructure from flood hazards.

Table 1. Mathematical equations used to calculate the hydrological characteristics of drainage basins by SCS method [1,12].

Equation	Coefficient	Equation Formula	Symbol Definitions
(3)	Concentration Time Gatton's Equation	$T_C = \frac{4A^{0.5} + 1.5L}{0.8H^{0.5}}$	A= Basin area km^2. TC= concentration time hr. L= length of main stream km. H= The difference between mean and the lowest level in the basin m.
(4)	Deceleration Time	$T_L = 0.6T_c$	TL= Deceleration time hr. TC= concentration time hr.
(5)	Duration of Excess Rain.	$T_r = 0.133T_c$	TC = concentration time hr. Tr = Duration of Excess Rain hr
(6)	Time of peak.	$T_P = \frac{T_r}{2} + T_L$	TP=time of peak hr. Tr Duration of Excess Rain hr TL= = Deceleration time hr.
(7)	Runoff (Berkeley Equation).	$R = (CIS)^{0.5}\left(\frac{W}{L}\right)^{0.45}$ $I = \left(\frac{RF}{1000}\right) \times \frac{(A * 1000000)}{1000000000}$	A= Basin area km^2. R=amount of runoff billion m^3 L= length of main stream km. S= slope of the basin km/m. I= annual rainfall billion m^3 C= Runoff coefficient =0.15 for arid and semi-arid areas. W= basin Width km. RF= rainfall mm.
(8)	peak flow for runoff.	$QR_p = \frac{0.208AR}{T_P}$	QP= peak flow m^3/sec. A= Basin area km^2. TP=time of peak hr. R=Runoff depth mm
(9)	velocity	$V = \frac{L}{3.6T_c}$	TC = concentration time hr. L= length of main stream km. V= velocity m/sec.

Hydraulic Design of concrete box culvert:

Complete analysis of the culverts hydraulics using basic equations can be difficult, because the flow conditions are constantly changing within the culverts. The flow can be partial or fill the entire culvert, depending on the condition of the watercourse at the inlet and outlet. Therefore, the design often relies on minimal hydraulic performance, which ignores temporary conditions that may provide better performance. This approach is characterized by the simplicity of design and ensuring adequate performance even in unfavorable conditions, such as a full-flow state that is best for manual calculations.

The flow modes in the outlet system needed to pass the flow through the culvert are calculated based on the energy balance, which includes the total energy minus the various losses. These losses include inlet losses, friction losses across the gate, and outlet loss, as well as losses from elbows, grating, junctions, and joints [13]. In this study, it was relied on that the flow of the entire length of the culvert, that is, the hydraulic condition of the pressurized flow. In order to find the dimensions of the box culvert from the height and width, it is necessary to calculate the maximum flow received by the culvert from the hydrological analysis of the drainage basin (Q_p m^3/sec) by using the flow with the losses Δh calculation equation [14]:

$$\Delta h = \left(\frac{Q_p}{(H*S)}\right)^2 \left(\left(\frac{n^2 \times L}{\left(\frac{H*S}{2(H+S)}\right)^{\frac{4}{3}}}\right) + \frac{K_e}{2g} + \frac{K_{ex}}{2g}\right) < (20\text{-}30cm) \quad (3)$$

where:
$\Delta h = head\ losses$ m
Q_p= peak flow m^3/sec
H= culvert height m
S= culvert width m

L= culvert length m
n= Manning coefficient (Table 2)
K_e= inlet friction coefficient losses (Figure 2)
K_{ex}= outlet friction coefficient losses (Figure 2)

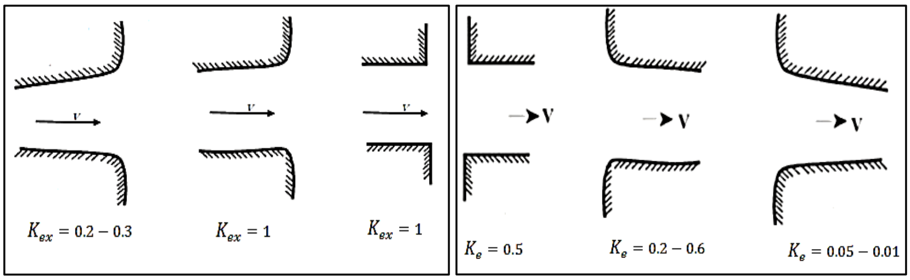

Figure 2: Different friction coefficients according to the type of entrance and exit of culverts [13].

Table 2. Roughness coefficient values (Manning coefficient) [14].

Manning coefficient n	Type of culverts connection	Material Type
0.011-0.013	Good connectivity and soft wall	Concrete Round Pipe
0.014-0.016	Good connectivity and rough wall	
0.016-0.017	Poor connection and rough wall	
0.015-0.2	Bad condition.	
0.014-0.018	Good connectivity and soft wall	Box Concrete
0.014-0.018	Poor connection and rough wall	
0.022-0.027	2.6x 0.5in	Square or round metal pipe or any other shape
0.022-0.025	6x 1in	
0.025-0.026	5x1in	
0.027-0.028	3x 1in	
0.033-0.035	6x 2in	
0.033-0.037	9x 02.5in	

Structural design of concrete box culverts

With this study, the LRFD (Load Reduction Factor Design) method was followed for the structural design procedures of the culverts with load factor and resistance, in line with AASHTO 3.4.1-2 [15], and to complete the structural design of the culvert, the loads applied to it must be determined, as follows (Table 3):

- The vertical distributed load by the weight of the paving material and soil as shown in, $g_1 KN/m^2$.
- The vertical distributed load from self-weight of the culvert, $g_2 KN/m^2$.
- The vertical live distributed load by Tandem Type B (AASHTO LRFD BDS) HL-93 truck with a weight, $P\grave{}_1 KN/m^2$ as shown in Figure3 [15].
- The vertical live distributed load of service and humans of the road above the culvert$\grave{P_2} KN/m^2$ according to design truck.
- The sum of distributed dead loads and live load above the culvert W KN/m^2,and the vertically distributed loads resulting from soil uplift pressure below the culvert $\overline{W} KN/m^2$ as shown in Figure4.
- The horizontal loads applied to the culvert sides from the soil, which are the lateral soil pressure loads e_1 KN/m^2, e_2 KN/m^2 and the initial lateral pressure e_0 KN/m^2 generated by the live loads as shown in Figure4.
- Ensure the ability of the soil($f_{llowable\ of\ soil}$) under the culvert to withstand the stresses it receives during operation f and maintenance, U where the maximum load by the soil is determined according to its type.

After determining the designed culvert loads, the structural analysis is carried out using one of the software dedicated to this, where the cross-section is modeled as a two-dimensional framework using the characteristics of the full cross-section as it is, and the movement of the lower slab is restricted. With this study, Robot2023 software was used to conduct the structural analysis and calculate moment and shear forces on the culvert and then calculate the reinforcing steel, its number and distribution, and draw the structural sections.

Table 3. Equations to calculate the loads applied to the box concrete culvert [14,15].

Equation No.	Load	Equation Formula	Symbol Definitions
(11)	$g_1 KN/m^2$	$g_1 = \frac{(W_1 + W_2) \times d \times \gamma_s}{2 \times W_2}$ $W_2 = d + W_1$	W_2= Width to which loads are transferred above the culvert m. W_1= Upper width of the road m. d =Height of backfilling materials above the culvert m. γ_S= Soil Density KN/m^3. g_1= weight of the paving material and soil load KN/m^2.
(12)	$g_2 KN/m^2$	$g_2 = \frac{1}{2}\frac{[(H_T \times D_T) - n(H^{`} \times D^{`})] \times \gamma_C}{N \times D}$ $D^{`} = D - t$ $D_T = N \times D + t$ $H_T = D + t$ $t = \frac{D}{12} or \frac{D}{(5\sim7)}$	γ_c= Concrete density KN/m^3 t = Culvert wall and slab thickness m. D= Culvert height and width m. D'= Inner culvert width m. H'= Inner culvert height m. N= Number of cells. H_T= Culvert total height m. D_T= Culvert total width m. g_2= culvert self-weight load KN/m^2 .
(13)	$P^{`}_1\ KN/m^2$	$P^{`}_1 = \frac{(1+I)(\sum P\ )}{L_1 \times L_2}$ $L_1 = 2 * (e + d)$ $L_2 = 3 * (b + d)$	L_1, L_2= Distances above the culvert to which design truck tire load has moved m. e =Width of the design truck tire 0.510 m. b= The thickness of the design truck tire 0.250 m. P= truck tire load KN.
(14)	$P^{`}_2\ KN/m^2$	$P^{`}_2 = \frac{P_{LL} \times W_1}{W_2}$	W_2= Width to which loads are transferred above the culvert m. W1= Upper width of the road m. P_{LL}= Service and human Distributed live load KN/m^2.
(15)	$W_{LL} KN/m^2$	$W_{LL} = P^{`}_2 + P^{`}_1$	$P^{`}_2$= Distributed live load corresponding to the design truck $KN/m^2$ $P^{`}_1$= distributed vertical Design truck tire load KN/m^2
(16)	W $\frac{KN}{m^2}$	$W = 1.25 \times (g_1 + g_2) + 1.75 \times w_{L.L}$	W_{LL}=The sum of the distributed live loads KN/m^2. g_1= paving materials vertical distributed load $\frac{KN}{m^2}$. g_2= Culvert Distributed self-weight load KN/m^2.
(17)	$\bar{W}\frac{KN}{m^2}$	$\bar{W} = 1.25 \times (g_1 + 2 * g_2) + 1.75 \times w_{L.L}$	W_{LL}=The sum of distributed live loads KN/m^2. g_1= weight of paving materials vertical distributed load $\frac{KN}{m^2}$. g_2=Self weight distributed load KN/m^2.
(18)	$e_1$and e_2 $\frac{KN}{m^2}$ $e_0 \frac{KN}{m^2}$	$e_1 = 1.3(\gamma_s(d)\frac{(1-\sin\emptyset)}{(1+\sin\emptyset)})$ $e_2 = 1.35(\gamma_s(d + Ht)\frac{(1 - \sin\emptyset)}{(1 + \sin\emptyset)}$ $e_0 = 1.5\left(P_{LL} \times \frac{(1-\sin\emptyset)}{(1+\sin\emptyset)}\right)$	d= Height of paving above the culvert m. γ_S= Saturated soil density KN/m^3. $\emptyset^0$ =Angle of soil friction. H_T= Culvert total width m. P_{LL}= service and human live Distributed load KN/m^2
(19)	Ensure that soil below the culvert can withstand the loads during operation f and maintenance U $f = g_1 + 2 \times g_2 + P^{`}_1 + \gamma_w\left(\frac{n \times D^{`} \times D^{`}}{D_t}\right) < f_{llowable\ of\ soil}$ $U = g_1 + 2 \times g_2 - \gamma_w H_t < f_{llowable\ of\ soil}$		

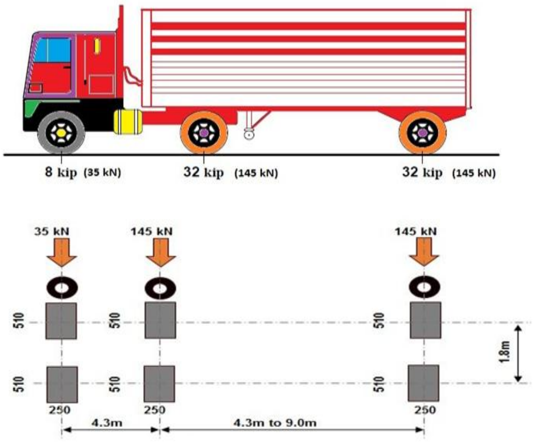

Figure 3: Truck design loads and its dimensions of AASHTO HL 93 [15].

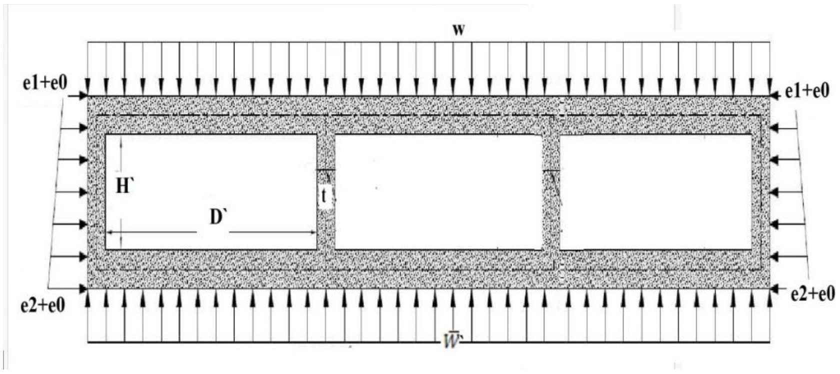

Figure 4: Box concrete culvert loads and dimensions.

Data used in the study

The reliable design of hydraulic structures, particularly culverts in dynamic environments such as Wadi Bab basin, necessitates a comprehensive and accurate set of input data. This section systematically outlines the diverse array of data sources and types that were accurately collected, processed, and utilized throughout this study. These data are:

- Two radar images of digital elevations study area, through the USGS website [16].
- The monthly total rainfall data available at NOAA NCEI and NOAA NWS for the time range from 1981 to 2022 are available for free (Figure5) [17].
- Requires structural and hydraulic design information for soil-type under the culvert and their resistance to loads, concrete and steel reinforcing resistance.

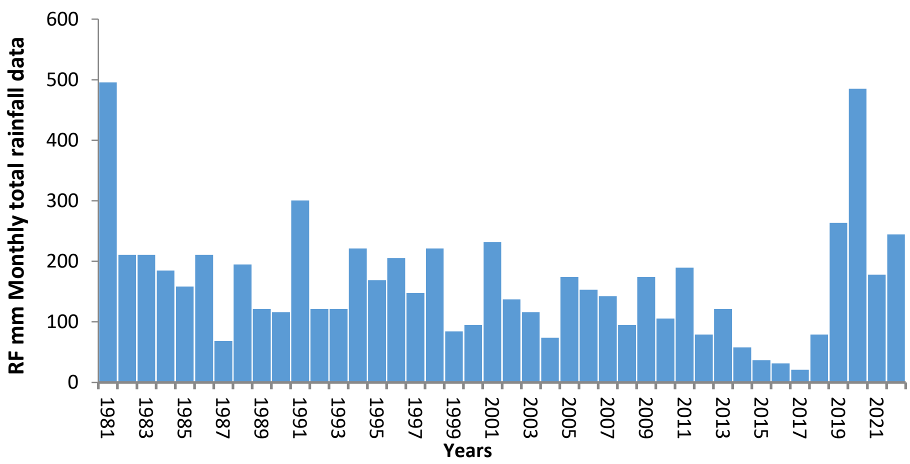

Figure 5: Monthly total rainfall data per year for WadiBab basin site, NOAA NCEI and NOAA NWS (1981 to 2022) [16].

Structural and Hydraulic design of the box concrete culvert on Selouk-Mesous Road, (WadiBab Basin)

The study area, located at the culvert's site, was initially identified to perform a morphometric analysis of the WadiBab basin and its streams. This basin directly impacts the Masous-Suluq road, where the culvert is strategically positioned at the basin's outlet to manage water flow. For the morphometric analysis, two radar images were used, which were obtained from the USGS website [17]. The images were processed using ArcGIS 10.8 to convert their geographic coordinates into UTM coordinates, specifically within the Libyan Geodetic Datum UTM 2006, Zone 34N. A digital elevation model (DEM) was subsequently generated for the area encompassing the WadiBab basin.

Any depressions or gaps within the resulting raster image were then filled to ensure the accuracy of the analysis. From this process, a digital analysis of the basin's main morphometric characteristics was conducted, and its cadastral and topographical features were determined. Using ArcGIS 10.8, the basin's cadastral properties, including its area, perimeter, stream length, and average width, were calculated. The natural land elevations of the WadiBab basin were then deduced from the digital elevation model. The complete results of this analysis are presented in Table 4 (Figure 6).

Table 4: Cadastral and Topographical Characteristics of WadiBab Basin Based on ArcGIS 10.8 software Results.

Coefficient	Value	unites
Basin Area A	1061.06	km^2
Basin perimeter P	250.07	Km
Length of main duct L	89.76	Km
Basin Width W	27.18	Km
Average natural land level H_{avr}.	278.93	m
Maximum natural land level H_{mzx}.	599	m
Minimum natural land level H_{min}.	109	m
slope S	50	Degree

Due to the absence of direct flood measurements in the WadiBab basin and the lack of a temporal distribution for a design storm, a statistical frequency analysis was performed. The maximum annual monthly rainfall totals for different return periods were calculated based on the statistical frequency distribution of the available data. The rainfall depth over the basin was then determined using equations that compute the return period, along with the probability and frequency of the rainfall event. Upon completion of these calculations, a probabilistic frequency chart was plotted (Figure 7), where the horizontal axis represents the return periods (T years) and the vertical axis represents the corresponding rainfall values (RFmm). The calculated values of the monthly total rainfall for various return periods are presented in Table 5.

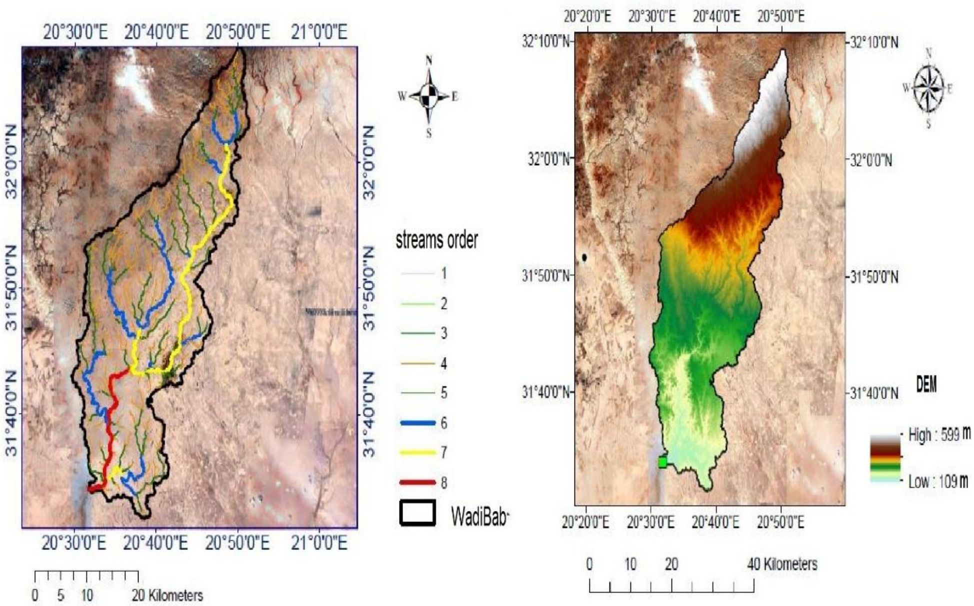

Figure 6: Natural ground level, and streams order in WadiBab basin according to the results of processing the (DEM) within the basin using ArcGIS 10.8 software.

Table 5: Rainfall data with return periods from 5 to 1000 years, for WadiBab basin sit, NOAA NCEI and NOAA NWS (1981 to 2022).

Return period T Year	Precipitation Rf mm
5	227.16
10	280.06
20	330.8
45	396.48
100	445.69
200	494.73
300	523.37
500	559.43
1000	608.32

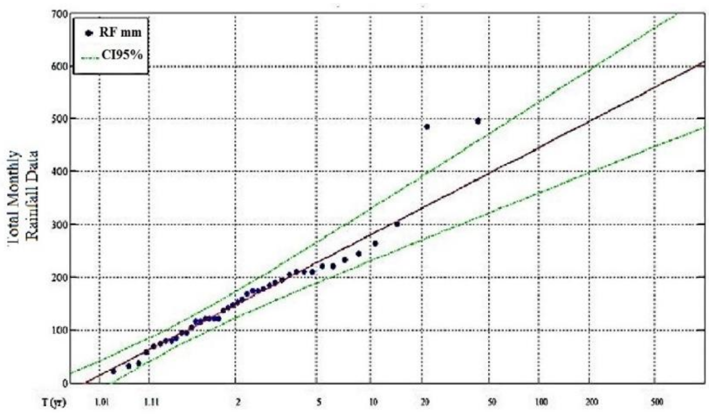

Figure 7: Probability curve for Total Monthly Rainfall Data for WadiBab basin area, period 1981to 2022.

The USA Soil Conservation Service (SCS) method stands as a strong and widely accepted approach for quantifying surface runoff, making it an indispensable tool for the hydrological design of infrastructure in ungagged basins. In this study, the SCS method will be systematically applied to compute the essential hydrological characteristics of WadiBab basin, which is critical for the appropriate design of a concrete box culvert located at its outlet along the Messous-Suluq road. Subsequently, employing design storm events derived from historical rainfall frequency analysis, the SCS method will facilitate the calculation of both the total runoff volume and, more critically, the peak flow rate expected at the culvert's location.

The precisely estimated peak flow rate will then serve as the primary input for the subsequent hydraulic design phase of the concrete box culvert. This direct application of the SCS method ensures that the culvert's dimensions including its cross-sectional area, height, and width are optimally sized to safely convey flood discharges, thereby mitigating flood risks, preserving the integrity of the Messous-Suluq road, and ensuring the long-term resilience of the infrastructure. The hydrological characteristics of the WadiBab basin, derived from the mathematical relations outlined in Table 1, are presented in Table 6.

Table 6. Hydrological characteristics of the WadiBab basin according to SCS method.

Coefficient	Value	Unit
RF Monthly maximum rainfall in a year Return period of 1000 years	608.3	mm
I rainfall intensity	0.679	billion.m^3
R surface runoff	0.436	billion.m^3
Qp peak flow.	5.678	m^3
Tc concentration time.	25.405	hr
TL deceleration time.	15.243	hr
Tr excess rain time.	3.379	hr
Tp Peak Time	16.932	hr
Runoff velocity	0.981	m/sec

Based on the drainage conditions of the culvert, the hydraulic design was developed under the assumption of a worst-case scenario, where the culvert is operating under full flow and pressurized

conditions. This approach ensures that the design can accommodate the entire flood discharge, with water pressure serving as the primary driver of flow within the culvert.
The design of the square box culvert at the outlet of the WadiBab basin was completed by following a set of design steps based on the following key inputs:

- The required design flow, or peak flow (Q_{PR}), was determined from the hydrological analysis of the WadiBab basin to be 5.6 m^3/sec (Table 6).
- The height and width of the culvert were calculated using an established hydraulic equation (Equation 10), assuming head losses of 0.25 m and a Manning's coefficient (n) of 0.016 for the concrete culvert (Table 2).
- The length of the culvert (L) was specified as the road width, 11 m.

Based on these design inputs, a three-cell concrete box culvert was selected as the optimal configuration to accommodate the anticipated flood discharges while ensuring structural and cost efficiency. The final design specifies a uniform square configuration for all three cells, with the height of each cell equal to its width, as illustrated in Figure 8.

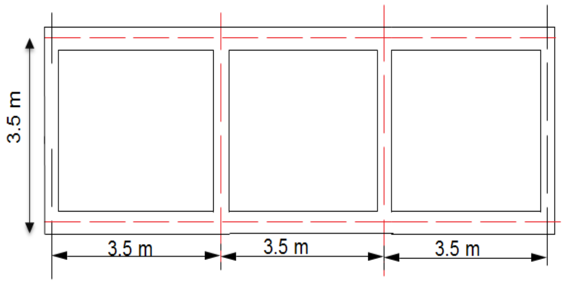

Figure 8: Dimensions of the designed concrete box culvert at Suluq-Mosus road.
With this study, the LRFD design method was followed for the structural design procedures of the culverts with load factor and resistance in line with AASHTO 3.4.1-2LRFD [15] according to the following data:

- The height of paving and backfilling materials above the culvert, d=1.4 m.
- The upper width of the road, w_1=11m.
- The width to which the loads are transferred above the culvert $W_2 = 12.4\ m$, road side slope in a ratio of 1:2.
- The materials to be used with the design from soil, concrete and water: (Saturated soil density $\gamma_S = 19$ KN/m^3 , soil friction angles $\emptyset^0 = 30^0$, $f_{llowable\ of\ soil} = 287\ Kpa$, concrete Density $\gamma_c = 24$ KN/m^3)
- The width and length of the square culvert D=3.5m c/c and its number N =3.
- The thickness of the walls of the square culvert t=0.50m.

Building upon the previously established design inputs, including the determined hydraulic dimensions and material specifications for the concrete box culvert situated at WadiBab basin outlet along the Messous-Suluq road, the critical step of quantifying the anticipated structural loads was undertaken. Utilizing the mathematical formulations and loading criteria detailed in Table 3, a comprehensive analysis was performed to calculate all applicable forces and pressures the culvert will experience throughout its service life. These calculations rigorously accounted for various load types, including self-weight, overburden pressure from soil fill, live loads from vehicular traffic, and hydrostatic pressure from internal water flow. The results of this intricate load determination process, outlining the specific magnitudes and distributions of these forces acting on the culvert structure, are meticulously presented in Table 7. This thorough assessment of design loads forms the indispensable foundation for the subsequent structural analysis and reinforcement detailing, ensuring the culvert's long-term stability and integrity under operational conditions.

Table. 7 Calculated loads applied to the box concrete culvert at Suluq-Mosus road With LRFD - AASHTO 3.4.1-2LRFD method.

Load	Value
Weight of paving material distributed load above the culvert.	g_1 =25.089 $\frac{KN}{m^2}$
Culvert self-weight distributed load.	g_2 =19.42 $\frac{KN}{m^2}$
Design truck Load.	$P`_1 = 34.4\ \frac{KN}{m^2}$
Distributed live load corresponding to the design truck.	$P`_2 = 8.87\ \frac{KN}{m^2}$
The sum of loads distributed vertically from dead and live load.	$W = 131.33\ \frac{KN}{m^2}$
Vertically distributed loads resulting from soil reaction below the culvert	$\overline{W} = 155.62\ \frac{KN}{m^2}$

lateral soil loads applied to both sides of the culvert Primary lateral pressure	$e_1 = 11.52\,\frac{KN}{m^2}$ $e_2 = 41.89\,\frac{KN}{m^2}$ $e_0 = 5\,\frac{KN}{m^2}$
stresses and loads it receives during operation and maintenance	$f = 122.41\,\frac{KN}{m^2}$ $U = 24.7\,\frac{KN}{m^2}$

Structural loads were applied to the culvert model for analysis using ROBOT2023 software. The loads were considered to be uniformly distributed across the culvert's width and length. This analysis determined the maximum moments and shear forces on the culvert's sections (Figures 9 and 10). The obtained results were then used to complete the structural design. Following the structural analysis, the design process was finalized based on the ACI code (Chapter 22 – Sectional Strength) [18]. A structural section of the culvert was then detailed to illustrate the distribution and dimensions of both longitudinal and transverse reinforcing steel, as shown in Figure11.

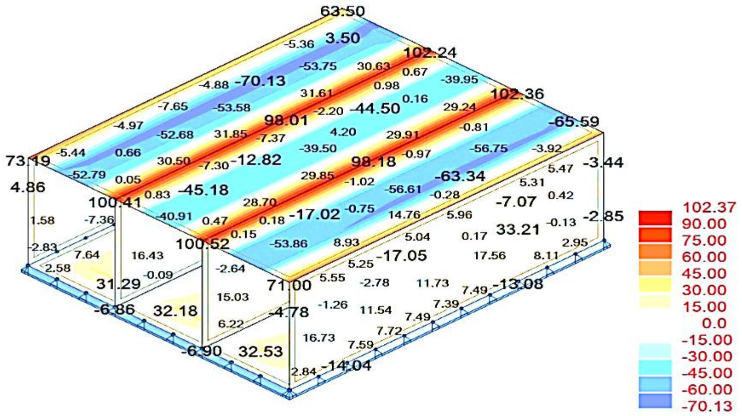

Figure 9: Moments distribution of the concrete box culvert, by Robot2023 software.

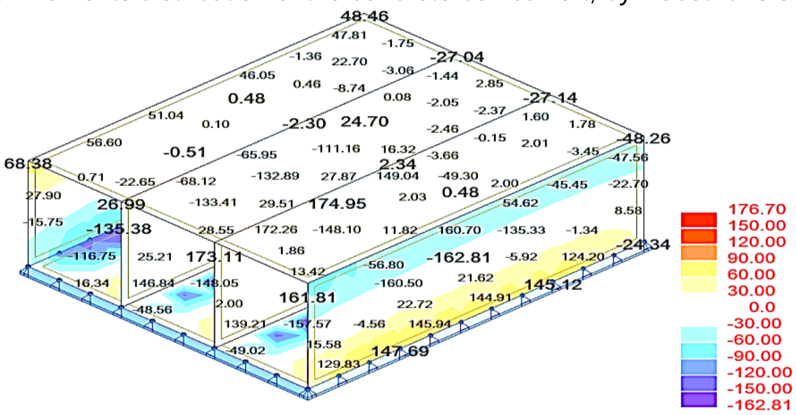

Figure 10: Shear forces distribution of the concrete box culvert, by Robot2023 software.

Table 8: Design details of the box culvert at Suluq-Mesus road.

Design	Square box phrase
Maximum moment M_u KN.m.	102.37
Maximum shear force V_u KN.	176.7
Resistance to concrete $f`_c$ KN/m^2	40
Reinforcing steel resistance $f_y \mathrm{KN/m^3}$	600
Concrete cover in the structural sections mm	70
Number of rebar bars with diameter Ø=18 mm	$4\emptyset18@180\mathrm{mm}$, Main Reinforcement Steel. $4\emptyset18@180mm$, *Cross-reinforcing steel.*

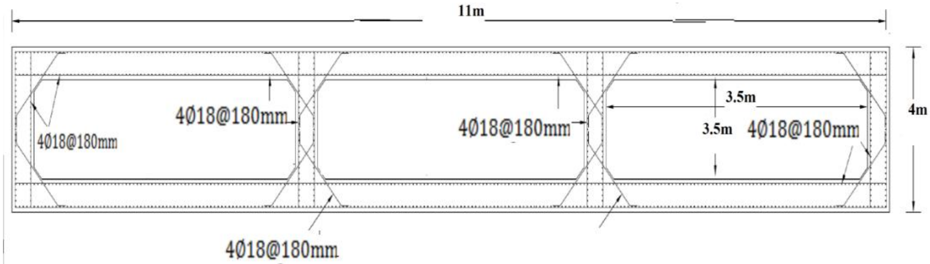

Figure11: Structural section of the culvert detailed of both longitudinal and transverse reinforcing steel.

Results Discussion

Based on the comprehensive analysis, the results confirm the flowing:

Based on the ArcGIS 10.8 software analysis, the cadastral and topographical characteristics of WadiBab basin have been accurately determined. The basin's significant scale is indicated by its large area of 1061.06 km², and a perimeter of 250.07 km. The main channel length was measured to be 89.76 km, with an average basin width of 27.18 km (Table 4). These findings highlight the basin's extensive dimensions, which are a critical factor in understanding its hydrological behavior. Furthermore, the topographical analysis revealed substantial elevation variations within the basin. The maximum and minimum natural land levels were recorded at 599 m and 109 m, respectively, with an average elevation of 278.93 m.

This wide range in elevation, combined with a steep average slope of 50 degrees, is a key indicator of the basin's high runoff potential. The steep slopes contribute to higher flow velocities, which must be accounted for in the hydraulic design of the culvert to ensure effective flood management. All of these morphometric characteristics provide the fundamental data necessary for the subsequent hydrological and hydraulic calculations.

Based on the statistical analysis of historical rainfall data, the precipitation values for the Wadi Bab basin have been determined for various return periods, as presented in Table 5. The analysis reveals a direct relationship between the return period and the magnitude of rainfall. As the return period increases, the corresponding precipitation depth also increases, which is a key indicator of flood risk. For instance, a rainfall depth of 227.16 mm is expected for a 5-year return period, whereas a much larger event of 608.32 mm is associated with a 1000-year return period. This significant increase in precipitation, over a range of nearly 381 mm, highlights the extreme rainfall events that must be considered in the hydraulic design of infrastructure, these values informing design decisions for the culvert, ensuring it can accommodate both frequent and rare, high-intensity storms.

Based on the application of the SCS method, the hydrological characteristics of WadiBab basin have been comprehensively determined and are presented in Table 6. These results are fundamental for the hydraulic design of the culvert, as they quantify the basin's response to a design storm event. The analysis, which was conducted for a 1000-year return period, identified a maximum monthly rainfall of 608.3mm. This rainfall event, when applied to the basin's characteristics, generates a total surface runoff volume of 0.436 billion m³. The most critical finding for the culvert design is the calculated peak flow (Qp) of 5.678 m³/s. This value represents the maximum discharge that the culvert must be designed to safely convey, ensuring it can accommodate the most severe flood events. Furthermore, the basin's hydrological response is characterized by a relatively long time of concentration (Tc) of 25.405 hr, which indicates a slow-responding basin, where flood peaks occur gradually. This is supported by a calculated runoff velocity of 0.981 m/sec, which reflects the overall flow behavior within the basin. The derived lag time (TL) of 15.243 hr and peak time (Tp) of 16.932 hr, providing essential data for designing a culvert that is appropriately sized for both the magnitude and duration of the anticipated flood.

A three-cell concrete box culvert was selected as the optimal configuration to accommodate the anticipated flood discharges while ensuring structural and cost efficiency. The final design specifies a uniform square configuration for all three cells, with the height of each cell equal to its width, as illustrated in Figure 10. A comprehensive set of design loads was calculated for the box concrete culvert using the LRFD-AASHTO 3.4.1-2 method. These loads, which are presented in Table 7, were quantified to ensure the culvert's long-term stability under all anticipated conditions. The total dead and live loads, were determined to include the culvert's self-weight, overlying paving material, and vehicular traffic, found to be 131.33KN/m². These values represent the minimum, constant forces that the structure must be designed to withstand. Furthermore, the effects of the surrounding soil were accounted for, with a lateral soil pressure of 11.52KN/m², and 41.89KN/m². being applied to the culvert's sides. The summation of these permanent, live, and lateral loads provides the essential input for the structural analysis. A rigorous consideration of all these forces ensures that the culvert's design is sufficient to guarantee its structural integrity and safety throughout its service life.

The structural design details for the box culvert are summarized in Table 8, outlining the key parameters that govern its capacity to resist anticipated loads. These details are a direct result of the structural analysis and are crucial for ensuring the culvert's long-term stability. The primary stresses that the culvert must be designed to resist are the maximum moment (Mu) and the maximum shear force (Vu). These values, which are determined from the applied dead and live loads, dictate the required amount of reinforcing steel in the concrete sections. The resistance provided by the concrete and the reinforcing steel is then calculated to ensure it exceeds these forces, thereby confirming the structural integrity of the design. Furthermore, a concrete cover of 70 mm was specified in the design. This detail is essential for providing adequate protection to the reinforcing steel from environmental corrosion and fire, ensuring the long-term durability of the structure. The final design also details the number and arrangement of the main and cross-reinforcing steel bars, with a diameter of Ø=18 mm, which are strategically placed to withstand the calculated moments and shear forces.

Conclusions and recommendations

This study successfully implemented a comprehensive and integrated approach for the hydraulic and structural design of a concrete box culvert at the outlet of WadiBab basin. The findings affirm that a rigorous, data driven methodology is essential for engineering strong infrastructure in ungauged basins. The final design, which incorporates hydrological and structural analyses, effectively addresses the site-specific challenges to ensure the long-term safety and performance of the culvert. The morphohydrological analysis of WadiBab basin revealed its extensive scale, with a large area of 1061.06 km^2 and a steep average slope of 50^0 degrees. These characteristics were found to be primary indicators of a high runoff potential, which must be accounted for in the design.

A statistical analysis of historical rainfall data was performed, identifying a direct relationship between return period and precipitation depth. A critical value of 608.32 mm was determined for a 1000-year return period, highlighting the need to design for extreme storm events. Using the SCS method, the hydrological response of the basin was quantified. The analysis yielded a peak flow of 5.678 m^3/s, which served as the fundamental input for the culvert's hydraulic design. A long time of concentration of 25.405 hr was also determined, indicating that the culvert must be able to handle a large discharge over an extended period. An optimal design was established as a three-cell concrete box culvert (3.5m X 3.5m), selected for its structural and cost efficiency.

All relevant loads were accurately quantified using the LRFD-AASHTO method, with a total vertical load of 131.33 kN/m^2 and lateral soil pressures surrounding 11.52KN/m^2, and 41.89$KN/m^{2,}$ being a key consideration. The final structural design was completed by detailing the reinforcement. It was confirmed that the culvert's sections are capable of resisting the calculated maximum moment and shear forces. The use of Ø18 mm reinforcing steel was specified to ensure the long-term durability and structural integrity of the culvert. Based on the findings and methodologies employed in this study, the following recommendations are proposed:

- Remote sensing and GIS should be integrated into future basin studies to provide a more efficient and accurate means of collecting morphohydrological data, especially in ungauged areas.
- The construction of dams for rainwater harvesting is recommended as a strategic measure to reduce total runoff volume, thereby further mitigating flood risks downstream.
- Regular and systematic culvert maintenance should be established as a standard procedure to ensure the continued hydraulic efficiency of the structure.
- For similar future projects, culverts should be strategically placed within the main valley courses to enhance their effectiveness in managing large-scale flood events
- Paying attention to the periodic maintenance of culverts, treatment of erosion, , and cleaning them from sediments and silt.

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