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Intelligent shells for Qanats: Integrating algorithmic design with traditional flood management, a case study from Baluchestan, Iran

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Abstract

Algorithmic design principles, combined with parametric modelling and optimization techniques, offer a promising approach to environmental challenges and renewable energy solutions. A pressing example is the water scarcity faced by many regions in the country. The Baluchestan region of Sistan and Baluchestan province exemplifies this challenge. Despite annual floods, strong currents damage Qanats (traditional water channels), rendering them unproductive. Utilizing and managing these floodwaters to recharge these ancient structures presents a potential solution. This study proposes an algorithmic and intelligent flood management Shell design inspired by traditional architectural patterns and adapted to Qanat structures. The Shell aims to regulate water inflow into Qanats, maximizing water capture while minimizing flood damage. The field data for this study was collected during archaeological fieldwork conducted in 2018 in Dezak Village, Saravan County, where ancient methods of directing floodwaters into Qanats were documented. Such insights highlight the potential of indigenous systems as sustainable alternatives to costly interventions like seawater transfer projects. The research employs Autodesk CFD, Rhino, and Grasshopper software to analyze the impact of the algorithmic flood management Shell design on Qanat inlets in the Dezak Village, Saravan county of Baluchestan Region. The study investigates whether algorithmic architectural principles can be effectively employed to address environmental challenges. The results demonstrate that by utilizing the region's traditional triangulation motifs, transforming them into a parametric structure, and incorporating algorithmic knowledge, it is possible to create climate-responsive shells that manage flood flow.

Keywords: intelligent shell, algorithmic design, architectural heritage, flood management, Qanat, Baluchestan, archaeology
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1 Introduction

The evolution of architectural design principles is a continuous narrative. From the pattern-driven approach of the classical era to the ideology-based architecture of the Middle Ages, each period has left its mark. The modern era saw a shift towards methodology and rationalism, followed by a renewed emphasis on form, structure, and the design process itself. Today's architects recognize design as a dynamic process, where the journey holds equal weight to the final destination. The advent of digital architecture in the 1990s further amplified this focus, paving the way for computers to become transformative tools in architectural practice [18]. Computational tools are now an integral part of architectural workflows. This, coupled with advancements in technology and various scientific disciplines, has given rise to the concept of algorithmic architecture. In essence, algorithmic architecture leverages a set of defined instructions, executed in a specific order, to solve a particular design problem. Think of it as a step-by-step recipe for architectural design [3].

This algorithmic approach has become a foundation language for various scientific fields. By translating their knowledge and processes into algorithms, scientists and researchers can leverage the power of computers to solve problems with high speed and accuracy. This interdisciplinary collaboration, termed "hybrid" or "convergent science," allows for knowledge exchange across disciplines such as mathematics, engineering, and biology, ultimately leading to architectural innovation [10]. Algorithmic architecture empowers architects to provide computers with initial design parameters. The computer then generates a multitude of design solutions, offering possibilities for complex forms that were previously difficult or expensive to create using traditional methods [3]. This translates to the ability to transform intricate design complexities into computational challenges, a powerful tool for today's architects [15]. The capabilities of algorithmic architecture can be harnessed to address pressing environmental challenges, particularly in the realm of water scarcity and renewable energy. Sistan and Baluchestan Province in Iran exemplifies this challenge. The region experiences severe water scarcity and electricity shortages despite annual floods that go untapped. Approximately 1.3 billion cubic meters of floodwater leave the province annually, a valuable resource that could be utilized. This research focuses on the Dezak Village, Saravan County within the Mashkil watershed. Here, we propose a solution that utilizes floodwater to address water scarcity and potentially even generate electricity for some areas. The key lies in Qanats, traditional underground water channels. Qanats are ingenious hydraulic structures that utilize gravity and natural slopes to transport water from mountainous areas to plains. Their unique design, with a continuous flow of water from the *KARIZ* (horizontal shaft), minimizes evaporation and ensures water sustainability, a critical feature in Iran's arid climate [9].

This study explores how algorithmic architecture can be applied to design an intelligent flood management shell for Qanats. The aim is to optimize water capture while minimizing flood damage. Parametric modelling and computational fluid dynamics (CFD) simulations will be employed to analyze the performance of these algorithmic shell designs. By harnessing the power of algorithmic architecture, we hope to promote sustainable water management practices in drought-prone regions.

2 The study area

Saravan County is a significant yet understudied region in the archaeology of southeastern Iran. Situated in the Sistan and Baluchestan Province, the county encompasses an area of 13,274 square kilometres (Fig. 1). Topographically, the region is characterized by mountainous terrain. The numerous surface and groundwater flows in the area have provided a suitable setting for the development of human settlements. This is evidenced by the numerous archaeological sites dating from prehistoric to Islamic periods that have been discovered in the region [13].

Dezak is an important village in the central part of Saravan County that has been inhabited throughout various periods in history. The village is located east of the city of Saravan and along the northern bank of the Mat Kur (Simish River) (Fig 2) [14].

In this article, by selecting Saravan County and the Dezak village to study the Qanat patterns of this region, a sample of Qanats has been simulated and analyzed. The Qanats in this area were identified and studied ethnographically during archaeological field studies in 2018 under the supervision of Mortazavi [13]. During his studies, he noticed that the ancient people of this land tried to manage the Qanats by directing floods into them and feeding them [14]. Following these studies, it was decided that in addition to better understanding this process, the experiences of the ancient people in using Qanats for flood management should be utilized and, by standardizing and modernizing their flood management methods, introduced to the scientific community. This research is the first of its kind in the region and country to explore the application of algorithmic architecture for flood management purposes. While previous studies have utilized algorithmic design for other architectural needs, the integration of algorithmic architecture with ancient and contemporary Qanats for flood management is a novel approach.

Figure 1: Morphological division of Saravan Region [11]

Figure 2: The Study Area, Dezak, Saravan [13]

3 Materials and methods

The research methodology employed in this study is a mixed-methods approach that combines field studies, Archival Method and Data Analysis.

3.1 Field studies

Field studies involved the collection of data through documentation techniques, such as photography, sketching, and note-taking. The researchers visited the Dezak Qanats in Saravan County to document its architectural features, including its layout, dimensions, and construction materials. They also interviewed local residents and experts to gather information about the Qanat's history, operation, and maintenance. These field activities were conducted within the framework of the Roubahak-Dezak Archaeological Project, a large-scale archaeological investigation that involved excavations at 10 ancient sites around the village of Dezak. The Qanats associated with these sites were also studied as part of the project [13].

3.2 Archival Method

Archival method involves the review of relevant literature, including books, journal articles, and online resources. The researchers examined historical texts, archaeological reports, and architectural treatises to gain a deeper understanding of Qanats and their significance in the region. They also reviewed contemporary research on algorithmic architecture, computational fluid dynamics (CFD), and flood management strategies.

3.3 Data collection and analysis

The data collected from field studies and archival method was analyzed using a combination of qualitative and quantitative methods. The qualitative analysis involved the interpretation of field notes, sketches, and photographs. The quantitative analysis involved the use of CFD simulations to evaluate the performance of the algorithmic Qanat Shell design.

The research involved the collection and analysis of architectural data and field information related to the Dezak Qanat in Saravan County, Sistan and Baluchestan Province, Iran. The specific steps involved in the data collection and analysis process are as follows:

3.3.1 Architectural data and information

- Review of historical documents and archaeological reports to gather information about the history, construction, and operation of the Dezak Qanat.
- Examination of architectural drawings and plans to understand the layout, dimensions, and structural details of the Qanat.
- Analysis of archaeological findings, including pottery fragments and other artifacts, to gain insights into the cultural context of the Qanat.

3.3.2 Field studies

- Documentation of the Qanat's architectural features through photography, sketching, and note-taking.
- Interviews with local residents and experts to gather information about the Qanat's current condition, usage patterns, and maintenance practices.
- Collection of hydrological data, such as rainfall patterns and flood records, to understand the Qanat's vulnerability to flooding.

3.3.3 Algorithmic shell design

- Identification of suitable design parameters for the algorithmic shell based on the architectural and field data.
- Development of an algorithmic design model using Grasshopper, a parametric modeling plugin for Rhinoceros 3D and 3Ds max
- Generation of multiple design options for the algorithmic shell based on the defined parameters.

3.3.4 3D Modeling and Simulation:

- Creation of a 3D model of the Dezak Qanat in Rhinoceros 3D and 3Ds max
- Integration of the algorithmic shell design into the 3D model of the Qanat.
- Simulation of flood flow over the Qanat and the performance of the algorithmic shell using computational Autodesk CFD software.

3.3.5 Data Analysis and Interpretation:

- Analysis of the CFD simulation results to evaluate the effectiveness of the algorithmic shell in reducing flood impact on the Qanat.
- Identification of the optimal design parameters for the algorithmic shell based on the simulation results.
- Drawing conclusions about the potential of algorithmic architecture for flood management in Qanat systems.

4 Qanat Architecture: A Sustainable and Social Answer to Flooding

Throughout history, architecture has served as a bridge between humans and their environment. John Ruskin [16] emphasized this by highlighting how architecture contributes to our mental and physical well-being, affecting our sense of power and enjoyment of space. This resonates deeply with contemporary environmental and sustainability movements, which advocate for architecture that fosters a harmonious connection with the natural world.

While aesthetics and form are undoubtedly important, Louis Sullivan's [19] famous adage "form follows function" reminds us that architecture serves a greater purpose than mere visual appeal. It is a human science, that actively shapes how people interact with their surroundings. Architects play a multifaceted role, not only expressing societal values but also influencing them. Historically, advancements in science, technology, and critical thinking have continuously redefined architectural paradigms, leading to increased specialization within the profession and a more departmentalized construction process.

4.1 Qanats: A Unique Architectural System with Social Benefits

Qanats exemplify a unique architectural system that masterfully manages human-environment interaction. These ingenious structures serve a dual purpose, displaying their unique nature from two perspectives. Firstly, they function as a remarkable feat of engineering, conquering the challenges of water scarcity in arid regions. In this role, Qanats act as a separate and unique architectural marvel in their own right. These underground structures consist of various components (Fig. 3), including vertical shafts for access, horizontal tunnels to tap into groundwater, and gently sloping channels to ensure water flow. This intricate network highlights the ingenuity of Qanat design (Behnia [4]; Boustani [5]). Secondly, Qanats can be seen as dependent structures, seamlessly integrating with surrounding architecture to provide a cool and refreshing environment. A prime example of this is the Ab Anbar, a traditional water reservoir that utilizes wind catchers and the cool air from the Qanat to create a passive cooling system [2]. Buildings were often constructed underground to leverage these cooler temperatures [20] (Fig. 4). Figure 4 illustrates the combined use of wind towers and Qanats. The diagram depicts the airflow within this system, explaining how this passive technique achieves cooling. This figure illustrates the Qanat's function as a dependent structure, seamlessly integrating with the surrounding architecture.

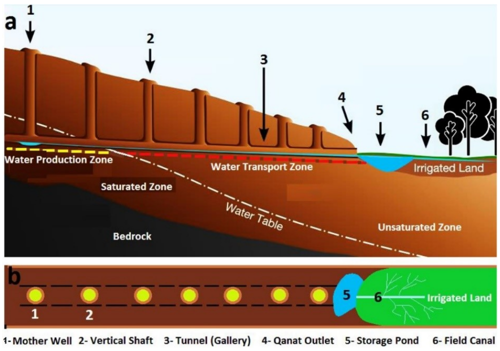

Figure 3: Schematic of a Qanat System: This figure illustrates a typical qanat system with two key perspectives: (a) a cross-section revealing the underground structure and (b) an aerial view showcasing the surface layout [17]

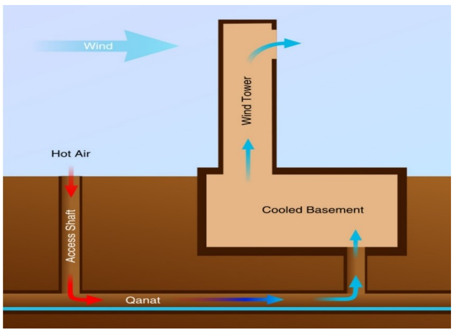

Figure 4: Diagram of a Qanat with Wind Tower [1]

Having established the remarkable qualities of Qanats as marvels of both engineering and social design, it is crucial to delve deeper into their intricate anatomy. These seemingly simple underground structures are, in fact, a testament to human ingenuity in subterranean architecture. Qanats, much like living organisms, rely on a network of interconnected parts to function. They comprise a sophisticated system of integrated components, each playing a vital role in channeling water from its source to parched landscapes. By dissecting each element, we gain a profound appreciation for the collective brilliance behind Qanat construction and operation, akin to understanding the intricate organs of a living entity. Qanat technology has evolved over the years, with new innovations being added all the time. These innovations are sometimes so creatively applied that they are truly astonishing. In the first instance, it is undoubtedly our duty to preserve these techniques and understand them in detail, and then to improve and update them to keep pace with the times [8].

4.2 Beyond water: mitigating floods through sustainable design

The benefits of Qanat architecture extend far beyond simply providing a water source and cooling buildings. These structures can also play a crucial role in managing the environment, particularly in regions prone to flooding. By channeling excess rainwater underground through the Qanat network, they can effectively mitigate floods, preventing potential devastation to communities and agricultural land. The brilliance of Qanat architecture lies not only in its unique structure, but also in its ability to tackle multiple challenges at once. It serves as a vital water source, fosters a sustainable cooling system, and even helps mitigate the risk of flooding. This approach aligns perfectly with the principles of sustainable design, offering a solution that works with nature, not against it.

Historical records attest that drought and water crises are not new phenomena in Baluchestan. Just as this region faces water scarcity today, similar conditions prevailed in the past. However, the solutions that were employed in the past to interact with nature, harness its resources, and put them to good use can still be applied today. Qanats were one way to utilize groundwater without causing significant damage to aquifers. The experiences gained by the region's inhabitants over years of interaction with the natural environment led to the development of indigenous solutions for the construction and efficient use of Qanats. One aspect that drew attention in the study of Dezak Qanats was their location along the region's seasonal watercourses (Fig. 5). This was not a coincidence; the inhabitants deliberately chose the locations of the Qanat wells [13]. This is further supported by the mention of the possibility of constructing qanats in the region's streams and rivers in Fermanfarma's travelogue of Baluchistan and Kerman [7].

4.3 Designing with Qanats: A sustainable approach to flood management

The future of flood management lies in innovative design solutions that leverage existing systems. By integrating new flood management shells with Qanat networks, we can create a sustainable and efficient approach to mitigating floods. These shells, strategically placed at flood-prone areas, can channel excess rainwater directly into the Qanat system, preventing surface flooding and minimizing damage.

This approach offers numerous advantages. Firstly, it utilizes existing infrastructure, reducing the need for extensive and potentially disruptive construction projects. Secondly, it promotes water conservation by directing floodwater towards a valuable resource. Finally, it reinforces the social benefits of Qanat architecture, fostering a more resilient and sustainable future for communities.

5 Analysis and simulation

The research methodology employed in this study involved the following steps:

1. **Structural Analysis of Qanats in the Saravan Complex:** A comprehensive structural analysis of the Qanats in the Saravan complex was conducted to gather detailed information about their construction, dimensions, and materials.

2. **Selection of a Qanat for Detailed Study:** One specific Qanat from the Dezak Village, Saravan complex was selected for in-depth analysis and 3D modeling (Fig. 5 & 6). This Qanat was chosen based on its representative characteristics and suitability for the study objectives.

3. **Hydrodynamic Modeling of Qanat Flow:** Computational fluid dynamics (CFD) simulations were performed using Autodesk CFD software to analyze and model the water flow within the selected Qanat. The simulations considered various flow conditions, including normal flow and flood conditions.

4. **Algorithmic Architecture Design for Qanat Inlet Cover:** An algorithmic architecture design was developed using Rhinoceros 3D and the Grasshopper plugin to create a dynamic and adaptive cover for the Qanat inlet. The design was inspired by ancient patterns and incorporated geometric principles to optimize flood and water management (Fig. 7).

5. **Performance Analysis of Qanat Inlet Cover:** The performance of the algorithmic Qanat inlet cover was evaluated using CFD simulations and structural analysis. The simulations assessed the cover's effectiveness in managing and directing floodwater into the Qanat while maintaining structural integrity under various flow conditions.

Figure 5: Dezak Qanat Wells and Watercourses [13]

Figure 6: The interior of the selected Dezak Qanat (Source: Authors)

Figure 7: Designs of exposed pottery from the Bampur Valley, Balucesstan [6]

5.1 Design of flood management shell

The initial step in the design of the Qanat inlet cover involved ideation and inspiration. The researchers sought to create a design that was not only functional but also aesthetically rooted in the cultural heritage of the Baluchestan region. Through extensive research and exploration, they identified ancient motifs found on ancient pottery as a source of inspiration (Fig. 7) (De Cardi [6]; Mortazavi [12]).

The selected ancient motifs [6], characterized by their intricate arrangement of lozenges, were analyzed and translated into a geometric representation using algorithmic design principles. The lozenges were divided into two halves and arranged within a hexagonal framework, forming a dynamic pattern that could adapt to varying flood conditions.

This algorithm is designed in two parts. The first part creates the overall geometry, or general structure, of the desired shell (Fig. 8).

The second part addresses pore closure through two sub-algorithms:

1. The initial image focuses on opening and closing pores to create an absorption point centered near each shell. By moving this point, the algorithm can determine the desired pore shape.

2. The other image considers the regional climate and sun position. It allows the shell's pores to be closed in six

sections, as shown in Figures 9 and 10.

The design draws inspiration from the rhombus motifs found on terracotta vessels of the Baluchestan region. These motifs are arranged in a hexagonal pattern during the design process. The resulting hexagonal shells feature two rhombus sections and six triangular sections, with each section potentially converted into a pore for water flow management (Figs. 11 & 12).

Aluminum or steel mesh can be used for the shell material due to its resistance to corrosion, rust, and water flow pressure.

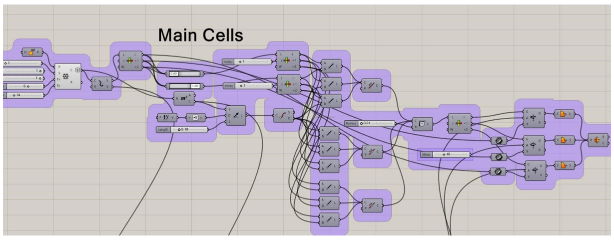

Figure 8: Algorithm for creating the basic structure of the shell managing flood flow (Source: Authors)

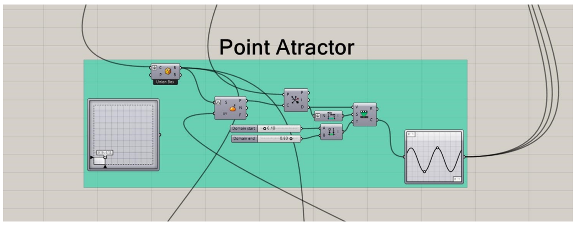

Figure 9: Algorithm of absorbing point to manage the movement of shell pores (Source: Author)

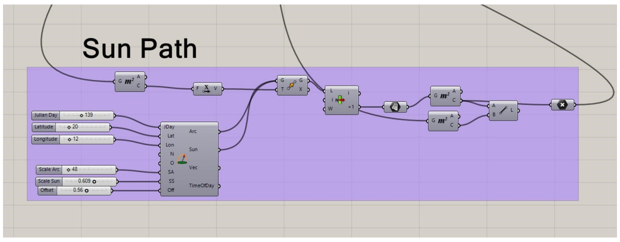

Figure 10: Algorithm of the path or position of the sun to manage the movement of the pores of the shell (Source: Authors)

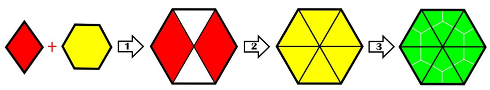

Figure 11: Concept process of flood management shell design (Source: Authors)

The algorithmic design incorporated two management mechanisms to regulate the opening and closing of the inlet cover's apertures:

1. **Central Managed Aperture Mechanism:** In this approach, a central point serves as the focal point for opening and closing the apertures. The position of this point can be adjusted to manage the size and shape of the openings, adapting to specific flood conditions.

2. **Sun-Responsive Aperture Mechanism:** This mechanism utilizes the position of the sun to dynamically manage the opening and closing of the apertures. The apertures are divided into six sections, each corresponding

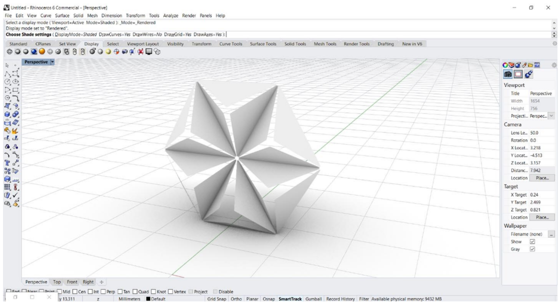

Figure 12: The shell designed in Rhino software environment (Source: Authors)

to a different time of day. The sun's position determines which apertures are open or closed, optimizing water management and flood management based on the time of day.

The resulting algorithmic Qanat inlet cover design is a hexagonal structure composed of two lozenge-shaped segments and six triangular segments. Each segment is equipped with adjustable apertures that can be managed using the two aforementioned mechanisms. The cover is constructed from durable materials, such as aluminum or steel mesh, to withstand corrosion, rust, and high water pressure. The algorithmic Qanat inlet cover is designed to withstand the forces of heavy floodwater while maintaining its structural integrity. The hexagonal framework and triangular segments provide a robust and stable structure, while the adjustable apertures allow for managed flow management without compromising structural stability. The proposed algorithmic Qanat inlet cover represents an innovative and adaptable solution for flood and water management in Qanat systems. Inspired by ancient motifs and incorporating algorithmic design principles, the cover effectively manages and directs floodwater into the Qanat while maintaining structural integrity under various flow conditions. This design has the potential to enhance the sustainability and resilience of Qanat systems in arid and flood-prone regions.

5.2 Analysis and Simulation of Qanat Inlet Cover Behavior under Flood Flow

In parallel with the design process, the structural integrity of the Qanat inlet cover was evaluated and analyzed using computational fluid dynamics (CFD) software to assess its behavior under flood flow conditions. The analysis involved simulating two scenarios:

Scenario 1: Flood Flow over Qanat Inlet Cover

In the first scenario, a flood-like flow was simulated over the Qanat inlet cover. The results, as illustrated in Figure 13 and Diagram **??** and the corresponding images, indicate that the cover's fractured structure effectively diverts floodwater to the sides. With 10% of the apertures open, the cover can reduce the incoming floodwater volume by up to 80%.

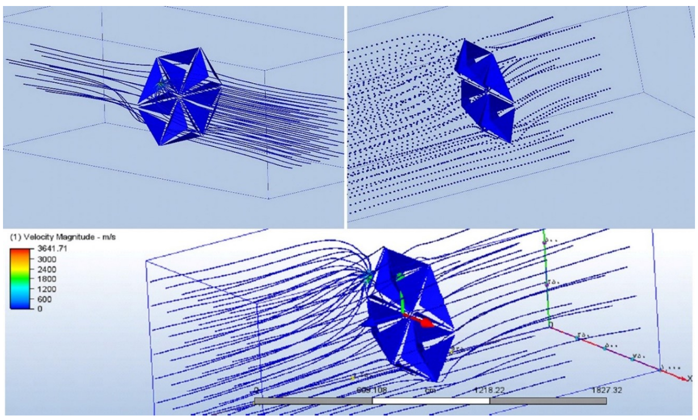

Figure 13: Images of the behavior of the shell against the flood flow in the software environment (Source: Authors)

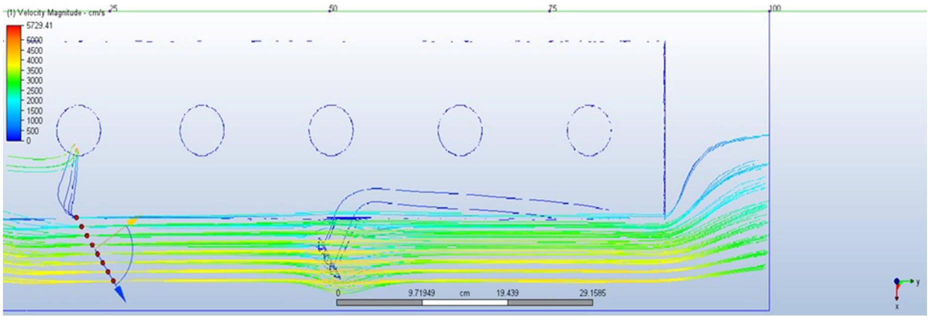

Diagram 1. Shell performance against flood flow (Source: Authors)

Scenario 2: Qanat Inlet Cover Performance on Qanat under Flood Flow

In the second scenario, the Qanat structure was simulated based on field data from the case study, and the designed Qanat inlet cover was placed at the Qanat inlet. The cover's performance on the Qanat under flood flow was analyzed using CFD software. The results revealed that the fractures on the cover's surface divert water outwards, allowing floodwater to enter the Qanat only through the apertures and in proportion to their opening size. The numerous apertures on the cover enable managed entry of a high volume of floodwater from multiple paths, preventing damage to the Qanat walls (Fig 14 & 15).

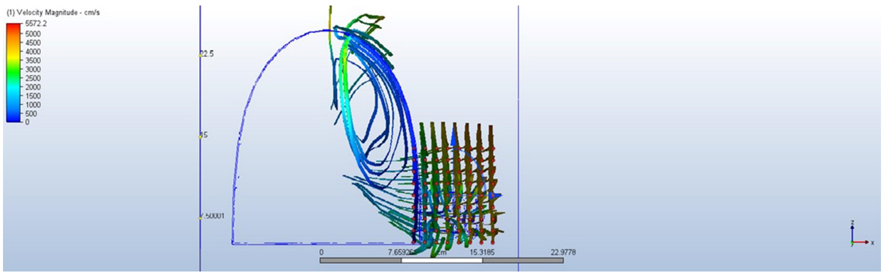

Figure 14: Top view of the algorithmic flood management shell behavior on the Qanat surface during flood flow. (Source: Authors)

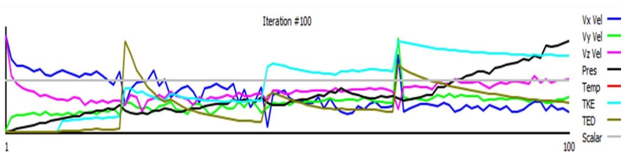

Figure 15: Side view of the algorithmic flood management shell behavior on the Qanat surface during flood flow. (Source: Authors)

By examining the performance of the designed Qanat inlet cover, several factors can be identified as influencing its effectiveness:

1. Structure inspired by the rich history and culture of Baluchestan
2. Regular and integrated geometry and structure
3. Fractured form that effectively diverts floodwater
4. Intelligent management of floodwater inflow rate
5. Management of floodwater and protection of qanat walls
6. Optimal performance under high flood pressures

6 Discussion and conclusion

The undeniable significance of Qanats in Baluchestan's water management system necessitates acknowledging the rich tapestry of traditional practices employed alongside them. Historically, effective water resource capture and utilization in Baluchestan relied on a multifaceted approach. Beyond the previously discussed Qanats, Baluchestan boasts a rich history of employing traditional structures for water management. Local communities utilized Degars (large, one-meter-walled pools) and Khoshābs (similar structures) to capture not only rainwater but also floodwater, complementing existing water resources [14]. These structures played a vital role in replenishing aquifers, ensuring a sustainable water supply.

However, the decline of the Khanate system (local leadership by Khans) shifted the focus towards maximizing agricultural production. Farmers, without the guidance of Khans, prioritized short-term gains, leading to a depletion of water resources in the aquifers. This highlights the importance of community participation and aquifer rebalancing for sustainable water management practices. Despite persistent droughts, Baluchestan experiences seasonal flooding due to the Indian Ocean's climate. Unfortunately, these valuable water resources often go uncaptured. Modernizing traditional flood management methods offers a viable solution to address water scarcity and promote watershed management through groundwater recharge. By utilizing management structures, floodwater can be effectively directed not only to Qanats but also facilitate infiltration into the highly permeable Baluchestan soil, replenishing aquifers.

This research project directly addressed water scarcity in Baluchestan by developing an innovative solution – an algorithmic Qanat inlet cover. Inspired by the intricate pottery motifs discovered at the Bampur archaeological site, the cover effectively manages and directs floodwater towards the Qanat inlet. This project exemplifies the potential of combining traditional architectural knowledge with modern technologies like algorithmic design. This study underscores the value of interdisciplinary approaches in tackling environmental challenges. By reviving and modernizing Qanats, water scarcity in Baluchestan can be addressed. This not only promotes sustainable water management but also has the potential to revitalize cultural heritage and potentially boost tourism in the region.

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