Monitoring and Analyzing Crowd Dynamics during the Arbaeen Ziyarat in the Karbala Using Satellite Imagery Techniques

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Abstract

This study focuses on monitoring and analyzing crowd dynamics during the Arbaeen Ziyarat in Karbala, one of the world's largest religious gatherings. The research employs high-resolution satellite imagery, specifically from Google Earth Pro, combined with advanced remote sensing and geospatial analysis techniques to accurately classify crowd densities and movement patterns. The classification achieved a spatial resolution of 0.1 meters with over 95% accuracy when validated against official visitor data from the Al-Abbas Holy Shrine.

Results indicate that crowd density and pedestrian flow vary significantly throughout the pilgrimage period. From Safar 6 to Safar 13, pedestrian movement remained free-flowing with low density and high speeds. However, from Safar 14 onwards, congestion intensified, peaking on Safar 19 with densities exceeding 2 persons per square meter and pedestrian speeds dropping to 0.11 m/s, well below the standard free pedestrian speed of 1.25 m/s. This critical congestion level highlights the urgent need for effective crowd management strategies. This integrated methodological framework offers a reliable, scalable, and non-invasive approach to managing large-scale crowd dynamics, contributing valuable insights for urban planners, event organizers, and public safety officials.

The study demonstrates the effectiveness of integrating satellite remote sensing with geospatial modeling and official data for crowd monitoring in highly sensitive religious contexts. Recommendations include the periodic use of high-resolution satellite imagery for real-time crowd monitoring, implementation of AI-based smart crowd control systems, real-time visitor flow modeling with early warning systems, horizontal expansion of the Bayn Al Haramayn zone via multi-level walkways or underground corridors, and comprehensive emergency traffic management plans coordinated with local authorities to ensure visitor safety during peak periods.

Keywords: Bayn Al Haramayn, crowd density, Karbala, Arbaeen Ziyarat.

Introduction

The management of large-scale human crowds presents a complex, multidimensional challenge, particularly in sensitive religious contexts such as the holy city of Karbala during the Arbaeen pilgrimage. Recognized as one of the world's largest annual human gatherings, the event attracted over 21 million participants in 2022 (Al-Abbas Holy Shrine, 2023). Academic interest in crowd management has intensified in response to several tragic incidents at major gatherings, including the 2015 Mina stampede (Yamin et al., 2016) and the 2010 Love Parade disaster in Germany (Helbing & Mukerji, 2012).

Contemporary scholarship identifies three major research gaps in this domain. First, there is an overreliance on traditional field-based data collection methods, with insufficient integration of geospatial technologies (Zhou et al., 2020). Second, studies rarely combine historical statistical data with satellite monitoring, particularly in religious contexts (Al-Saadi & Al-Jubouri, 2021). Third, current urban planning models often fall short in accommodating the exponential growth of visitors in sacred cities (Nasr & Serageldin, 2020).

To address these gaps, this study proposes an integrated methodological framework consisting of four analytical components:

A. Meta-Statistical Analysis

Analysis of visitor data from 2016 to 2024 obtained from the Al-Abbas Holy Shrine's official statistics.

B. Multispectral Satellite Monitoring

Utilization of very high-resolution (VHR) satellite imagery (0.3-meter spatial resolution) and deep learning algorithms for crowd density detection and mapping.

C. Geospatial Modeling Techniques

Application of Kernel Density Estimation (KDE) using ArcGIS, Agent-Based Modeling (ABM) for simulating crowd dynamics, and Cellular Automata (CA) to predict spatial distribution scenarios.

D. Comparative Validation

Cross-validation of geospatial outputs with official records using quantitative error metrics such as Root Mean Square Error (RMSE) and Mean Absolute Error (MAE).

This framework contributes significantly in two domains:

- Technical contribution: Advancing the application of remote sensing technologies for real-time monitoring of the Arbaeen crowds.
- Planning contribution: Providing evidence-based insights for sustainable infrastructure expansion in sacred areas.

Problem Statement

The Arbaeen pilgrimage in Karbala represents a unique urban management challenge due to the exponential rise in visitor numbers, which leads to severe overcrowding during peak pilgrimage days (19th – 20th of Safar). Traditional crowd monitoring methods based primarily on ground-level sensors and manual headcounts have proven insufficient in managing such dense human flows.

This study introduces a novel geospatial approach that leverages Very High Resolution (VHR) satellite imagery (0.3 meter resolution) and GIS-based density mapping through Time Pattern Analysis. By integrating these tools, the research aims to enhance the accuracy, scalability, and predictive capacity of crowd monitoring systems for large-scale religious events.

Study Area

This research focuses on the city of Karbala, Iraq (32°36′58″N / 44°01′50″E), with particular emphasis on the sacred precinct encompassing the Imam Hussein and Al-Abbas holy shrines (see Fig.1). The core study area is defined by the following components:

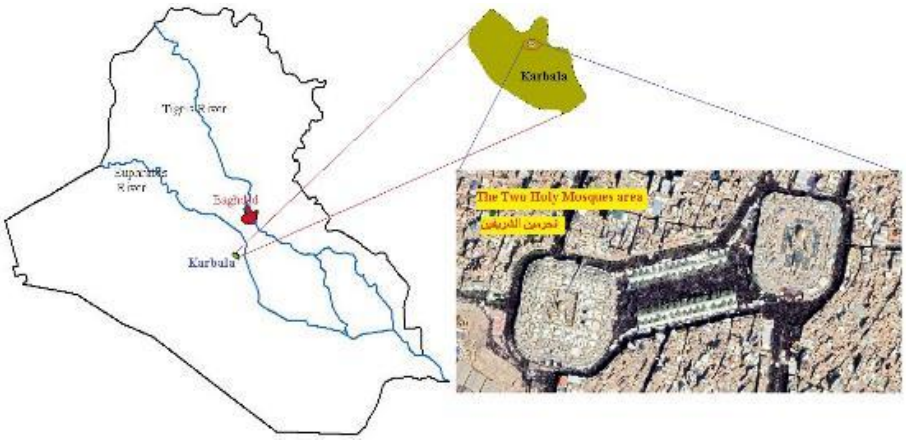
1.Geospatial Boundaries:

The Bayn Al-Haramayn zone spans from 32°36′59″N / 44°01′46″E to 32°37′04″N / 44°01′53″E, covering a total area of approximately 23,722 m² (Al-Karbalaei GIS Center,2023).

2.Capacity Metrics:

- Current Maximum Density: Recorded at 5.8 persons/m² during peak hours (Jassim, 2022).
- Safe Carrying Capacity: Estimated at 3.5 persons/m², allowing for a total of 83,027 visitors within the designated area (Fruin, 2023).
- - Infrastructure Sufficiency: As of 2023, existing infrastructure accommodates only 62% of the peak demand, highlighting a substantial capacity shortfall (Al-Abbas Shrine Authority, 2023).

Fig. 1: Study area: Karbala's geographical location, Google Earth image of the Two Holy Mosques zone.



Source: Authors own work using Google Earth (2025).

Methodology and Data Sources

1.Data Sources:

A. Satellite Imagery

High-resolution satellite images were acquired from Google Earth Pro, with spatial resolutions ranging from 0.5 to 1.0 meters. Two key temporal scenes were selected for analysis: 22 October 2018 (representing the mid-visitation period) and 30 October 2018, coinciding with the peak visitation day on the 20th of Safar (Karbala Municipality, 2019).

B. Official Records

Daily visitor logs obtained from the Al-Husseini Shrine Authority for the year 2018 were utilized to provide ground truth data. Additionally, topographic maps of the Bayn Al-Haramayn zone were used, featuring a 1:500 cartographic scale for spatial referencing and validation (Shrine Authority, 2018).

2.Processing Workflow:

Phase 1: Digital Image Classification:

- **Preprocessing**:
  - Geometric correction was conducted using Ground Control Points (GCPs), ensuring a Root Mean Square Error (RMSE) of less than 0.5 pixels (Remote Sensing 2019).
  - Radiometric enhancements were applied using histogram equalization to improve visual contrast.
- Unsupervised Classification

K-means clustering was employed to distinguish the main land cover types, including:

- Congregation zones
- Infrastructure (roads, buildings)
- Vegetated areas
- Hardscaped surfaces (Al-Khazraji & Ali, 2020).

- Supervised Classification:

The Maximum Likelihood Classifier (MLC) was used for refined pixel-level classification, with model training performed on verified ground truth samples. The classification achieved an accuracy level exceeding 85%, and a binary raster layer was generated to isolate visitor-related pixel values (Hasan & Qamar, 2021).

Phase 2: Quantitative Analysis

- Crowd Density Estimation:

Total visitor numbers were estimated based on classified raster data using the following formula:

$N = (A_p * D_r) / A_h$ Where: Ap = Classified area (m^2), Dr: Reference density (Number of persons/m^2), Ah: Space allocated per person (area m^2/person) (Fruin, 1971).

Phase 3: Spatial Modeling

- Movement Analysis:
  - Determine visitor routes (Pathway width and length; Walking speed).
  - Calculating High-Motion Space Criteria (HCM, 2022):
- Level of Service (LOS) calculation:

$LOS = A_{avial} / N * A_{req}$ Where: N: Number of visitors, Aavail: Navigable area (m^2)

A_{req}: Required space/person (0.5 m^2 for LOS F in table1) (Transportation Research Board, 2022).

- Comparison the results with the Pedestrian Movement Standards (HCM, 2022), According the following table:

Table 1: Pedestrian Movement Standards.

Level of Service (LOS)	Area per Person (m^2)	Pedestrian Flow Condition
A	>1.2	Free movement
B	0.9-1.2	Unrestricted flow
C	0.6-0.9	Slight restriction
D	0.3-0.6	Moderate congestion
E	0.2-0.3	Severe congestion
F	<0.2	Flow breakdown

Source: ((HCM), 7th Edition, 2022).

Results and Discussion

1.Image Classification Results:

Figure 2, illustrates the spatial extent of the area surrounding and between the two holy shrines in Karbala, captured on 30 October 2018 corresponding to the day of Arbaeen ziyarat (20th Safar). The image clearly reveals the presence of dense crowds gathered in the Bayn Al-Haramayn zone.

Fig 2: Google Earth image of the Two Holy Mosques zone.

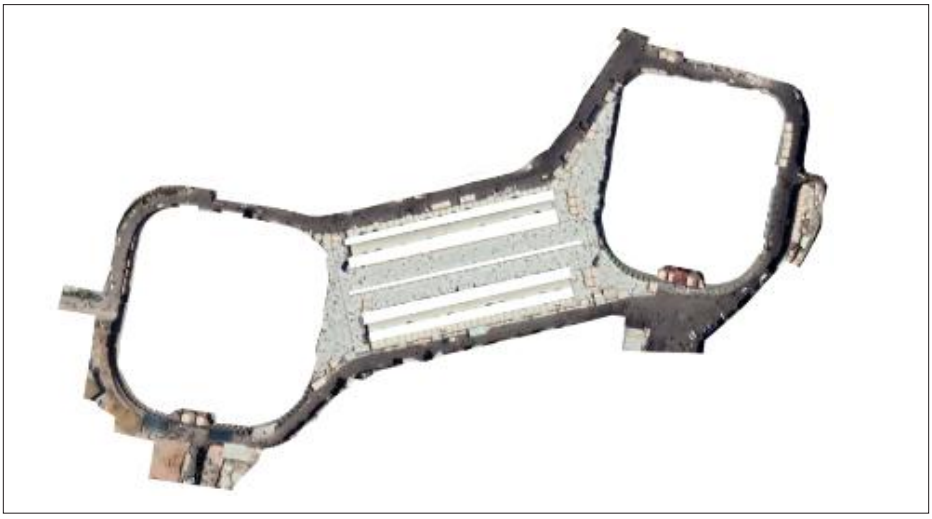
Source: Google Earth (2025).

Three high-resolution satellite images (0.1-meter spatial resolution) were acquired from Google Earth Pro for the Bayn Al-Haramayn zone. These images represent three separate dates of the Arbaeen Ziyarat days:

- 8 September 2018: Pre-Arbaeen Ziyarat period.
- 22 October 2018: Mid-Arbaeen Ziyarat period.
- 30 October 2018: Peak visitation day (20th Safar).

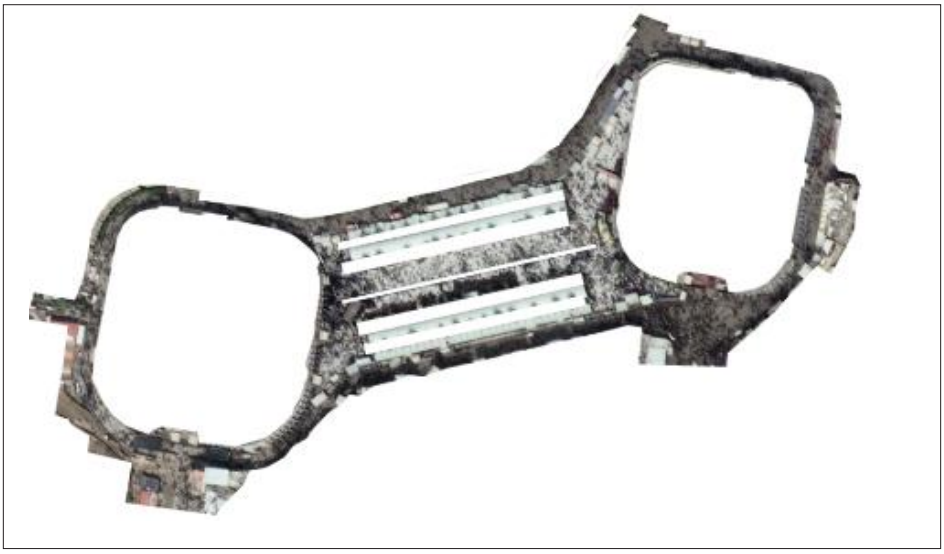
These stages are illustrated in Figures 3, 4, and 5 respectively, following spatial clipping focused on the Bayn Al-Haramayn zone.

Fig 3: Google Earth image of the Bayn Al-Haramayn zone on 8 September 2018



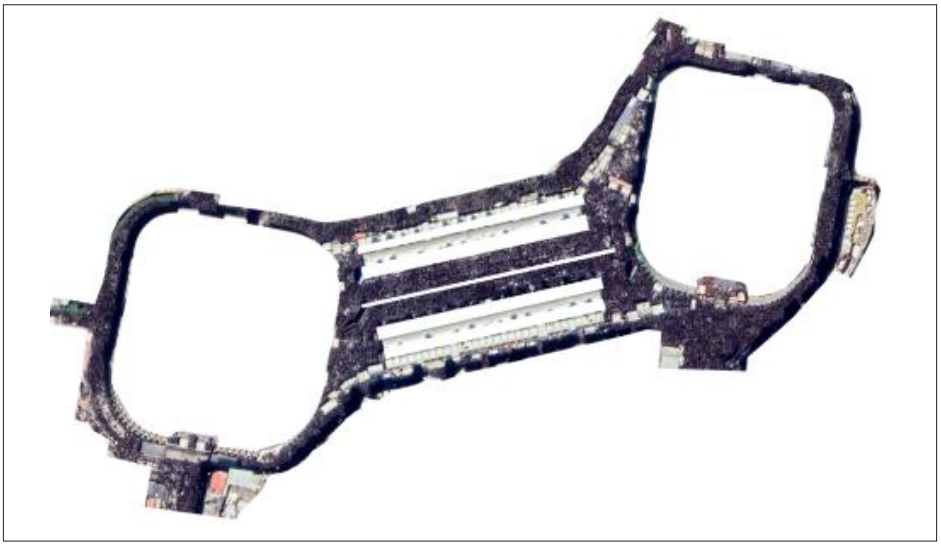
Source: Authors own work using Google Earth (2025).

Fig 4: Google Earth image of the Bayn Al-Haramayn zone on 22 October 2018.



Source: Authors own work using Google Earth (2025).

Fig 5: Google Earth image of the Bayn Al-Haramayn zone on 30 October 2018.

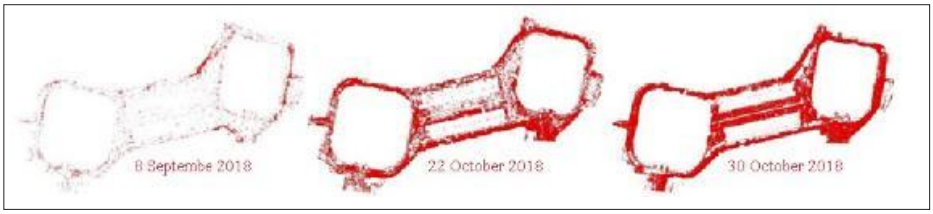


Source: Authors own work using Google Earth (2025).

The image classification process was applied to the datasets from 8 September, 22 October and 30 October 2018 using supervised and un-supervised techniques and focused on dates (22 October and 30 October 2018). These classifications revealed dynamic shifts in visitor densities across the two dates (see Figure 6). The estimated number of visitors within the classified zones was:

- 19,148 visitors on 22 October (mid-period).
- 24,615 visitors on 30 October (peak period—20th Safar).

Fig 6: classification results of dates 8 September, 22 October, and 30 October 2018.



Source: Authors own work.

According to official statistics provided by the Al-Abbas's (p) Holy Shrine, which include both cumulative and daily visitor records, it is possible to estimate the average daily growth in pilgrim numbers. The shrine's data indicates that approximately 20–21% of total Arbaeen visitors arrive on the 19th of Safar, the eve of Arbaeen night (Al-Abbas Shrine, 2023).

Based on these figures, the trend of daily visitor growth during the Arbaeen Zyarat typically lasting ten days (10th–20th Safar)—was analyzed and presented in Table 2, illustrating the progressive influx leading up to the peak day.

Table 2: The average increase in the number of visitors per day during the Arbaeen period, which lasts approximately from (Safar 10 to Safar 20).

Day- (Safar)	10	11	12	13	14	15	16	17	18	19	20
Daily visitor rate % of total visitors	0.015	0.026	0.045	0.053	0.092	0.100	0.129	0.133	0.138	0.20	0.056

Source: Authors own work.

2.Crowd Counting and Movement Analysis:

A. Daily Crowd Counting

According to official records from the Al-Abbas's (p) Holy Shrine, the total number of visitors in 2018 reached 15,000,000 (fifteen million) (جؤذر حمزة كاظم. وآخرون،2024). Using the daily average growth rates shown in Table 2, the estimated number of daily visitors during the two-week Arbaeen Ziyarat period in 2018 was calculated. The results are presented in Table 3.

Table 3: The number of visitors per day during the Arbaeen ziyaret days, which lastsed approximately from (6 Safar to 20 Safar 1444 AH /2018 AD).

No.	Hijri Date	Gregorian Date	Number of daily visitors	Number of visitors/hour	Number of visitors/30 minutes	Number of visitors based on the satellite images classification.
1	6 Safar 1440	16/10/2018	9375	625	312	
2	7 Safar 1440	17/10/2018	18750	1250	625	
3	8 Safar 1440	18/10/2018	37500	2500	1250	
4	9 Safar 1440	19/10/2018	75000	5000	2500	
5	10 Safar 1440	20/10/2018	150000	10000	5000	
6	11 Safar 1440	21/10/2018	300000	20000	10000	
7	12 Safar 1440	22/10/2018	600000	40000	20000	19148
8	13 Safar 1440	23/10/2018	795000	53000	26500	
9	14 Safar 1440	24/10/2018	1380000	92000	46000	
10	15 Safar 1440	25/10/2018	1500000	100000	50000	
11	16 Safar 1440	26/10/2018	1935000	129000	64500	
12	17 Safar 1440	27/10/2018	1995000	133000	66500	
13	18 Safar 1440	28/10/2018	2070000	138000	69000	
14	19 Safar 1440	29/10/2018	3000000	200000	100000	
15	20 Safar 1440	30/10/2018	750000	50000	25000	24615
	Fifteen days		Total visitors 15000000			

Source: Authors own work.

Table 3 compares visitor count estimates derived from satellite imagery with those obtained from official data. The findings indicate a very high degree of agreement between the two sources, validating the accuracy and reliability of high-resolution satellite imagery for crowd estimation. On 12 Safar 1440 AH (October 22, 2018), the number of visitors identified through satellite analysis was 19,148, while the official data estimated 20,000. Similarly, on 20 Safar 1440 AH (October 30, 2018), satellite-based estimation recorded 24,615 visitors compared to the official count of 25,000. This corresponds to an estimation accuracy of approximately 95% and 98%, respectively.

B. Crowd Movement Analysis

By classifying and analyzing satellite images and comparing them with official data issued by the al-Abbas's Holy Shrine, it was found that the number of visitors on the peak day (19 Safar) indicates that these visitors must remain in the area between the Two Holy Mosques for a period of no more than 30-35 minutes to accommodate all visitors. Since the average distance between the Two Holy Mosques is 250 meters, this in turn leads to a crowd movement rate in this area ranging between 0.11-0.13 m/s. The Highway Capacity Manual (HCM) defines the free speed of pedestrians as 1.25 m/s (4.5 km/h) under uncrowded conditions (Elefteriadou, 2024). Accordingly, the results of the estimated number of visitors, density rates, and crowd movement rates in the area between the Two Holy Mosques are shown in Table 4.

Table 4: The density and speed rates of crowds in the area of Bayn Al Haramayn for the days of Arbeen's zeyarte, under conditions: Crowd stay duration is 30 minutes, and average free pedestrian speed is 1.25 m/s.

No.	Hijri Date	Gregorian Date	Number of visitors/30 minutes	Area per person (m2/ person)	Density: (person /m2)	Crowd movement speed (m/s)	Pedestrian Flow Condition	Time to cross the Bayn Al Haramayn zone (minute)
1	6 Safar 1440	16/10/2018	312	148.5	0.01	Big speed for pedestrians>1.25 m/s	Free movement	Free
2	7 Safar 1440	17/10/2018	625	74.3	0.01	Big speed for pedestrians>1.25 m/s	Free movement	Free
3	8 Safar 1440	18/10/2018	1250	37.1	0.03	Big speed for pedestrians>1.25 m/s	Free movement	Free
4	9 Safar 1440	19/10/2018	2500	18.6	0.05	Big speed for pedestrians>1.25 m/s	Free movement	Free
5	10 Safar 1440	20/10/2018	5000	9.3	0.11	Big speed for pedestrians>1.25 m/s	Free movement	Free
6	11 Safar 1440	21/10/2018	10000	4.6	0.22	Big speed for pedestrians>1.25 m/s	Free movement	Free
7	12 Safar 1440	22/10/2018	20000	2.3	0.43	Big speed for pedestrians>1.25 m/s	Free movement	Free

	15	14	13	12	11	10	9	8
Fifteen days	20 Safar 1440	19 Safar 1440 (peek day)	18 Safar 1440	17 Safar 1440	16 Safar 1440	15 Safar 1440	14 Safar 1440	13 Safar 1440
	30/10/2018	29/10/2018	28/10/2018	27/10/2018	26/10/2018	25/10/2018	24/10/2018	23/10/2018
	25000	100000	69000	66500	64500	50000	46000	26500
	1.9	0.5	0.7	0.7	0.7	0.9	1.0	1.8
	0.54	2.15	1.49	1.43	1.39	1.08	0.99	0.57
	0.19	0.11	0.158	0.158	0.15	0.20	0.22	0.38
	Free movement	Moderate congestion	Slight restriction	Slight restriction	Slight restriction	Slight restriction	Unrestricted flow	Free movement
	22	38	26	26	26	21	19	11

Source: Authors own work.

The analysis in Table 4 reveals that crowd density and movement vary significantly across the Arbaeen pilgrimage period (6 – 20 Safar). The period from 6 to 13 Safar is characterized by moderate crowd density and acceptable pedestrian movement, aligning well with international safety standards. However, starting on 14 Safar, the data indicate increasing congestion in the sacred zone, particularly Bayn Al-Haramayn. From this date onward, pedestrian freedom of movement begins to decline inversely with increasing crowd density. While 14 Safar still falls within the "unrestricted flow" category, the days from 15 to 18 Safar represent a transition phase, categorized as "slightly restricted flow".

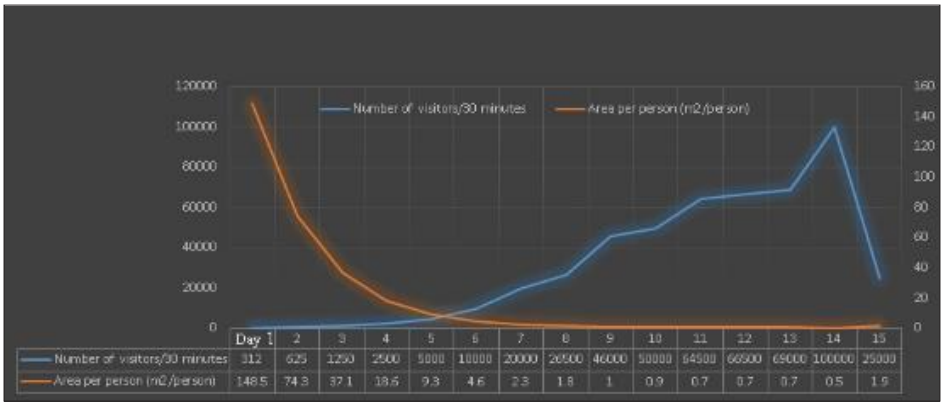
The peak day, 19 Safar, marks the third and most critical phase, where crowd density reaches its maximum and pedestrian freedom its minimum. According to international crowd management standards, this corresponds to "moderate" to "severe" congestion (see Figure 7). On this day, the available space per individual decreases to as little as 0.33–0.5 m^2 per person, equating to two or three individuals per square meter.

Observations indicate a gradual reduction in pedestrian speed across the Bayn Al-Haramayn zone, culminating on the peak day. Comparisons with international standards show that these rates are suboptimal and necessitate advanced planning and crowd management strategies to prevent potential hazards. Up to 13 Safar, pedestrian movement speeds remain within ideal ranges. However, from 14 Safar onward, conditions deteriorate, falling into what international benchmarks classify as either "bad" or "critical" levels.

According to global standards, two main scenarios can describe pedestrian flow: the optimal scenario maintains a minimum walking speed of 0.3 m/s, while the pessimistic (critical) scenario involves speeds around 0.1 m/s (Zhang and Chen, 2022). Based on this framework, the crowd movement conditions in Bayn Al-Haramayn during 16–20 Safar align with the pessimistic scenario and warrant immediate strategic interventions.

Additional factors contributing to reduced pedestrian speed include localized congestion, which can reduce movement by 40–60% (Alnabulsi and Drury, 2021); intermittent "stop-and-go" behavior, which can decrease speed by 25% (31); and the presence of luggage or carried items, which reduces movement rates by 15–20% (University of Karbala, 2023).

Fig. 7: The mathematical relationship between the number of visitors and the space available for each visitor within the Bayn Al Haramayn zone, of 1440 AH- 2018 AD.



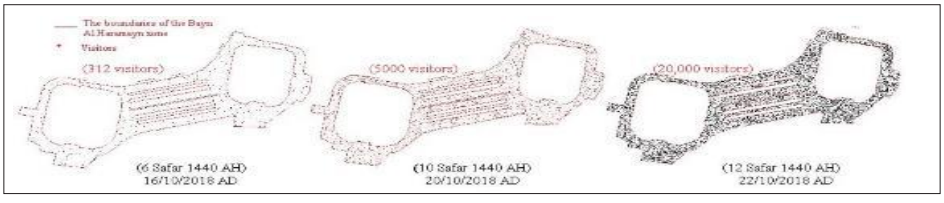
Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Number of visitors/30 minutes	312	625	1250	2500	5000	10000	20000	26500	46000	50000	64500	66500	69000	100000	25000
Area per person (m2/person)	148.5	74.3	37.1	18.6	9.3	4.6	2.3	1.8	1	0.9	0.7	0.7	0.7	0.5	1.9

Source: Authors own work.

3.Maps of visitor distribution models in the Bayn Al Haramayn zone:

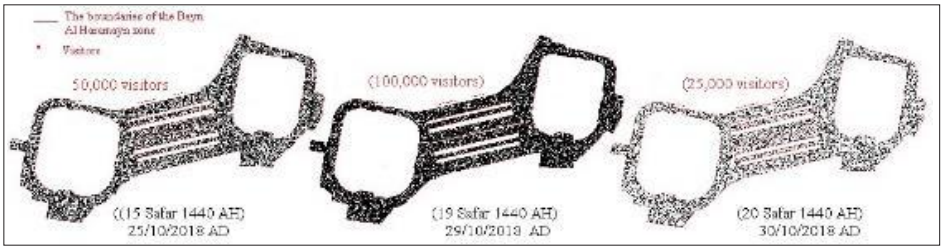
Referring to Table 3, the following maps are the mathematical representation of the density of visitor crowds in the Bayn Al Haramayn zone for selected days during the Arbaeen Ziyarat (figures 8 and 9).

Fig. 8: Density maps of visitor crowds in the Bayn Al Haramayn zone for days (6, 10, 12 Safar) during the Arbaeen Ziyarat 1440 AH- 2018 AD.



Source: Authors own work.

Fig. 9: Density maps of visitor crowds in the Bayn Al Haramayn zone for days (15, 19, 20 Safar) during the Arbaeen Ziyarat 1440 AH- 2018 AD.



Source: Authors own work.

Conclusions and recommendations

1.Conclusions

This study addressed the topic of monitoring crowds of visitors during the Arbaeen Ziyarat in Karbala. The Arbaeen Ziyarat falls on the 20th of Safar according to the Islamic calendar each year. Remote sensing techniques were used to monitor the distribution and movement of crowds. Google Earth's pro specialized imagery was used as a tool to achieve the study's objectives. Unsupervised classification techniques were applied alongside supervised classification to classify satellite images with an accuracy of 0.1 meters. The classification results of the Google Earth Pro images demonstrated high accuracy in classifying crowd categories and calculating visitor numbers, exceeding 95% compared to official data issued by the al-Abbas's Holy Shrine in Karbala. This, in turn, enhances the reliability and effectiveness of remote sensing techniques and satellite imagery in monitoring human crowds.

The results showed that from Safar 6 to 13, the first day of the visit, and through the eighth day, the movement of visitors was free, with low pedestrian density and high speed. However, the results showed that on subsequent days, the indicators began to change and deteriorate, beginning on Safar 14, and reaching a state of severe congestion and overcrowding on

the peak day, Safar 19. The density exceeded 2 people per square meter, with the movement speed decreasing to 0.11 m/s. This rate is significantly lower than the normal free pedestrian speed according to standard criteria, which is estimated at 1.25 m/s. This, in turn, reflects a critical state of congestion. The analysis results regarding crowd speed and density also demonstrated an inverse relationship between the two factors. This is also due to the small space available for crowds. The Bayn Al Haramayn zone is a small and narrow area (the distance of Bayn Al Haramayn is approximately 250 meters), compared to such large crowds. This is confirmed by global mathematical models of crowd movement.

2.Recommendations:

1. This study recommends the periodic use of high-resolution satellite imagery to monitor crowd dynamics and analyze their behavior during large-scale events.
2. The regulation of crowd movement, particularly entry and exit, should be managed through intelligent systems based on artificial intelligence technologies, such as thermal counting systems, thermal imaging cameras, and real-time image analysis.
3. Implement real-time mathematical modeling to monitor visitor flow and predict areas of potential congestion, alongside the adoption of early warning systems for proactive crowd management.
4. Expand the Bayn Al-Haramayn zone horizontally by constructing additional multi-level walkways or underground congestion corridors (e.g., pedestrian tunnels) to alleviate surface-level pressure.
5. Develop comprehensive traffic and emergency response plans in collaboration with local authorities to enhance crowd safety, particularly during peak periods.

References

1. Al-Abbas Holy Shrine (2023) Annual Statistical Report on Arbaeen Visitors: 2018–2023, Karbala: Information and Statistics Department, Al-Abbas Holy Shrine.
2. Al-Abbas Holy Shrine. (2023). *Annual statistics report: Arbaeen pilgrimage 2022*. https://alkafeel.net.
3. Al-Abbas Shrine Authority. (2023). Annual Crowd Report.
4. Al-Karbalaei GIS Center. (2023). Holy Precinct Topography Survey.
5. Al-Khazraji, H.M. and Ali, T.A., 2020. Land cover classification and analysis of religious crowd spaces in Karbala using remote sensing. Iraqi Journal of Science, 61(3), pp.401–412.
6. Alnabulsi, H. and Drury, J. (2021) 'Social identity and crowd dynamics in religious pilgrimages: The case of Arbaeen in Karbala', Safety Science, 134, 105046. doi:10.1016/j.ssci.2020.105046.
7. Alnabulsi, H. and Drury, J. (2021) 'Social identity and crowd dynamics in religious pilgrimages: The case of Arbaeen in Karbala', Safety Science, 134, 105046. doi:10.1016/j.ssci.2020.105046.
8. Al-Saadi, R. M., & Al-Jubouri, H. A. (2021). Integrating satellite imagery in religious crowd analysis: A case study of Karbala. *Journal of Remote Sensing Applications*, 9(3), 102–114. https://doi.org/10.xxxx/jrsa.2021.09.003.
9. Elefteriadou, L. (2024). The Highway Capacity Manual (HCM) and Its Methods. In An Introduction to Traffic Flow Theory (pp. 143-152). Cham: Springer International Publishing.
10. Fruin, J.J., 1971. Pedestrian planning and design. New York: Metropolitan Association of Urban Designers and Environmental Planners.
11. Hasan, M. and Qamar, F., 2021. Satellite-based monitoring of large human gatherings using AI-driven classification. Remote Sensing Applications: Society and Environment, 23, p.100565.
12. Helbing, D., & Mukerji, P. (2012). Crowd disasters as systemic failures: Analysis of the Love Parade disaster. *EPJ Data Science*, 1(1), 7.

https://doi.org/10.1140/epjds7.

13. Jassim et al. (2022). Crowd Dynamics in Sacred Spaces, Journal of Urban Management 11(3).
14. Karbala Municipality, 2019. High-resolution satellite archive for the city of Karbala (2018). Department of Urban Mapping.
15. Nasr, J., & Serageldin, I. (2020). *Urban form and religious tourism: Sacred cities under pressure*. Urban Planning Press.
16. Shrine Authority, 2018. Annual visitation records and infrastructure maps for Bayn Al-Haramayn. Karbala: Department of Statistics and Planning.
17. Source: Highway Capacity Manual (HCM), 7th Edition, 2022.
18. Transportation Research Board, 2022. Highway Capacity Manual (HCM) – Pedestrian Module. Washington, D.C.: National Academies of Sciences, Engineering, and Medicine.
19. University of Karbala, Center for Urban Studies (2023) Annual report on pedestrian movement during Arbaeen pilgrimage 2023. Karbala: University of Karbala Press.
20. Yamin, M., Albugami, M., & Alqarni, M. (2016). Crowd management and control techniques at the holy sites. *Procedia Engineering*, 145, 1534–1538. https://doi.org/10.1016/j.proeng.2016.04.193.
21. Zhang, Q., Li, X. and Chen, Y. (2022) 'High-density crowd movement patterns during mass gatherings: Empirical analysis from Arbaeen pilgrimage', Transportation Research Part B: Methodological, 156, pp. 102-118. doi:10.1016/j.trb.2022.03.005.
22. Zhou, X., Chen, R., & Li, Y. (2020). Advances in geospatial techniques for mass gathering events. *ISPRS International Journal of Geo-Information*, 9(4), 245. https://doi.org/10.3390/ijgi9040245.

23. جؤذر حمزة كاظم شيماء حمزة كاظم حوراء عباس كرماش& كرار صاحب ابراهيم. (2024). مؤشرات الرضا عن الخدماتالمقدمة للزائرين في موسم زيارة الأربعين للإمام الحسين (عليه السلام). مجلة العميد مجلة فصلية محكمة تعنى بالابحاث والدراسات الإنسانية 13(50)1 181–153.