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Research on the Reform of Architectural Acoustics Education Based on Noise Measurement and Simulation

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Simulation,
Site Planning,
Design Optimization,
Building Renovation,
Teaching Reform

ABSTRACT

This paper aims to enhance students' comprehensive practical abilities in the field of architectural acoustics through teaching reforms, especially in terms of how to effectively apply acoustic knowledge to the entire process of site planning and architectural design. In response to the disconnect between theory and practice in traditional architectural physics courses, this paper proposes the introduction of a combined experimental teaching model that integrates field noise measurement and simulation. Through this model, students can not only master the basic theories and principles of architectural acoustics but also deeply understand the impact of noise on the functional quality and environmental quality of architectural spaces through on-site noise monitoring and digital simulation technologies. The course content covers noise control and management from the early stages of building planning, design optimization, to later stages of building renovation, with a focus on the application of architectural acoustic simulation techniques in practical design. This approach not only helps students improve their practical application of architectural acoustics knowledge but also cultivates their ability to address noise issues effectively during the design process, ultimately promoting the organic integration of architectural design and environmental sustainability. The teaching reform proposal put forward in this paper seeks to enhance students' ability to solve practical problems by combining theory and experimentation and provide theoretical and technical support for acoustic optimization in future architectural designs.

1. Introduction

With the increasing emphasis on the "human-centered" concept, architectural education and practice are increasingly focused on enhancing human life quality, particularly in terms of environmental comfort, health, and sustainability. In architectural design, traditional considerations such as aesthetics, functionality, and structure can no longer meet the comprehen-

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sive demands of modern society for built environments. Noise pollution, as a key factor influencing environmental quality, directly affects people's physical and mental health, work efficiency, and overall quality of life. This issue has become even more critical with the rapid urbanization process, where problems like traffic noise and construction noise have grown more severe. To address this challenge, effectively controlling and optimizing the noise environment in architectural design has become an important topic in modern architectural education. Architectural noise issues are not only a technical challenge but also involve the consideration of the overall performance of the built environment, including the organic integration of lighting, thermal, and acoustic environments. How to improve the comfort and sustainability of architectural spaces through rational design and technological means has become an indispensable part of modern architectural design education. In this process, the application of architectural environmental simulation technology has become increasingly essential in both teaching and practice. Particularly, the use of computer-based simulation and virtual reality technologies has provided students with more intuitive and precise tools for understanding architectural environments.

Several scholars have actively explored the application of architectural environmental simulation technologies. Hong, for example, introduced building performance simulation technology and utilized the Ladybug and Honeybee software platforms to optimize simulations of building energy consumption and lighting environments, aiming to cultivate students' ability to enhance environmental comfort through simulation techniques in architectural design [1]. Through simulation technology, students not only gain a deeper understanding of the basic principles of thermal and lighting environments in architecture but also effectively improve their practical application skills in actual design, thereby enhancing teaching effectiveness. Similarly, Bian Yu and others emphasize the importance of experimental teaching methods. They argue that through hands-on practice and personal experience, students can systematically master the knowledge of architectural optics, innovate lighting environment teaching models, and enhance their practical application abilities in lighting design [2]. In the field of architectural acoustics, Zhu Xiangdong used an experiential teaching approach and assessed students' understanding of architectural acoustics knowledge before and after the course through surveys. He found that this method effectively helped students establish foundational concepts in architectural acoustic design and improved their ability to solve practical acoustic problems in architectural design [3]. Shao Teng and others proposed a problem-oriented teaching model, incorporating research-based problem modules to encourage students to explore and analyze autonomously. This not only helped students better understand architectural acoustics theory but also strengthened their research capabilities. With modern technologies such as virtual simulation and performance simulations, students can understand and apply architectural acoustic design principles in realistic experimental environments [4]. Furthermore, Yue Siyang and Li Xinxin combined methods like soundscape, sound-walk, and subjective evaluation to design an outdoor sound environment experiment based on both objective and subjective analysis. This helped students gain a more intuitive understanding of environmental noise and realize that the sound environment is not only determined by the volume of noise but also closely related to the types and composition of sounds, which in turn produce different physiological effects. This experimental model strengthened students' comprehensive awareness of the impact of sound. Further innovation can be seen in the application of virtual simulation technology [5]. Li Lei et al. introduced a virtual simulation platform into acoustic experiments by integrating LabVIEW-based AD2 handheld labs and virtual reality (VR) technology. This allowed students to break through the constraints of experimental space and time, offering a more vivid and interactive learning experience. Virtual simulation technology not only breaks the limitations of experimental equipment and venues but also significantly reduces the difficulty of experimental operations, helping students better understand abstract acoustic concepts while enhancing their practical skills and innovative thinking. Additionally, the virtual simulation teaching model for environmental noise monitoring has made significant progress [6] [7]. Li Wenwen, through the reform practice of the virtual simulation experiment on environmental noise monitoring at Anhui Normal University, explored how to combine traditional teaching methods with modern simulation technologies. By implementing a progressive virtual simulation system, this approach enhances students' practical skills. This model overcomes the limitations of time and space, allowing students to gain a deeper understanding of the specific operations of noise monitoring without external environmental restrictions, and become more proficient in environmental noise analysis in real-world scenarios [8] [9]. The issue of campus noise has also received widespread attention. Huang and others used a noise propagation model to develop a noise map for university campuses, aiming to identify and analyze the campus noise environment. By adjusting the distance between buildings and traffic routes or adopting reasonable soundscape designs, noise interference with teaching activities can be effectively reduced, thereby improving the acoustic environment of the campus. This research provides feasible solutions for campus noise control and optimization, offering theoretical and practical support for future similar studies [10] [11].

Through the continuous advancement of these teaching innovations and practices, the environmental and acoustic education in architecture has gradually moved towards a more specialized and refined direction, particularly with significant breakthroughs in the application of modern technological methods. Methods such as virtual simulation, experiential teaching, and experimental learning have not only effectively enhanced students' practical abilities and innovative thinking but also provided new perspectives and tools for architectural design and environmental optimization. As these educational models continue to develop and improve, future architectural design is expected to achieve more intelligent and personalized advancements in areas such as noise control and environmental optimization.

2. The Significance of Integrating Noise Measurement and Simulation in Design

In modern urban environments, noise has become an environmental nuisance that cannot be overlooked. Although noise does not directly threaten life safety, its impact on human health is profound and long-lasting. Prolonged exposure to excessive noise levels can lead to hearing loss and is also closely associated with the occurrence of cardiovascular diseases. High-quality acoustic environments play a crucial role in enhancing the quality of life. However, the harmful effects of noise are often difficult to detect or ignore, and its negative impact is challenging to completely eliminate. Therefore, addressing noise control and simulation in architectural design is of paramount importance. This is particularly significant in architectural education, where the integration of noise measurement and simulation technologies plays a key role in enhancing students' understanding and practical skills.

Currently, many architectural schools focus heavily on fostering students' imaginative thinking and artistic creativity, often at the expense of emphasizing the application of architectural engineering techniques and the analysis of real-world environmental issues [12]. In the process of architectural design, noise is not merely a standalone design element; it is also closely related to factors such as the building's materials, structure, and layout. Traditional architectural acoustics experiments (e.g., measuring sound pressure levels, reverberation time, and sound absorption coefficients) provide students with fundamental data on noise control. However, these experiments are typically conducted in isolation, lacking a comprehensive understanding of the relationships between various architectural physical elements. Therefore, the integration of noise measurement and simulation can help students better grasp the holistic approach to architectural acoustics design during the learning process.

In simulation exercises, students are able to analyze the factors of noise propagation, building layout, material selection, and other elements in an integrated manner, developing a comprehensive understanding of the physical environment of buildings and enhancing their ability to address complex environmental issues. With the rapid development of information technology, modern tools such as virtual laboratories, virtual simulation systems, and immersive software have provided richer educational resources and methods for architectural teaching. These technologies can break the limitations of traditional teaching, offering students a more vivid and intuitive learning experience. Through virtual simulation, students can not only simulate noise propagation in buildings in real-time, but also directly experience the impact of noise on different spatial layouts and material configurations within a virtual environment. This immersive experience deepens students' understanding of noise control technologies, cultivating their ability to apply various technical solutions to solve environmental problems in actual architectural design, thus driving profound transformations in experimental teaching concepts, methods, and approaches in architectural education.

Future work for architecture students will not only involve creative design, but also addressing a variety of practical environmental challenges. Although current experimental teaching does not place particular emphasis on hands-on skill development, it does demand rigorous design capabilities and the ability to analyze and address environmental problems. Through the combination of noise measurement and simulation, students can not only master simple experimental methods and data processing techniques, but also enhance their sensitivity to environmental noise issues and cultivate comprehensive environmental analysis and problem-solving skills. Throughout the teaching process, experiential learning enables students to gradually establish foundational concepts in architectural acoustics design, understand the importance of noise control, and apply their knowledge in subsequent design practices to propose feasible solutions for environmental improvement.

With the growing promotion of green building and sustainable design concepts, noise control has become an indispensable aspect of architectural design. The integration of noise measurement and simulation allows students to approach the design process from a sustainable development perspective, considering how to minimize noise in architectural design while optimizing building structure, material selection, and layout to maximize the acoustic quality of both indoor and outdoor environments. Simulation not only helps students predict noise levels but also provides opportunities to compare and optimize various design solutions, promoting architectural designs that are more focused on ecological and human-centered needs, thereby enhancing the environmental friendliness and comfort of buildings. With the rapid development of virtual reality (VR) and artificial intelligence (AI) technologies, the combination of noise measurement and simulation has entered a new phase. Virtual reality technology offers an immersive learning experience, allowing students to personally experience the effects of noise control and simulate noise propagation under different design scenarios in a virtual environment. This immersive experience enhances students' understanding of noise issues and helps them make more precise judgments in design. Artificial intelligence, on the other hand, can optimize design solutions by analyzing large amounts of noise data, automatically adjusting building layouts and material configurations to achieve more effective noise control. The integration of VR and AI technologies into noise simulation not only increases the interactivity and scientific nature of architectural teaching but also drives architectural design toward more intelligent and personalized solutions.

In conclusion, integrating noise measurement and simulation into architectural education not only addresses the current shortcomings in practical training but also enhances students' design capabilities in noise control. Through modern information technology and innovative teaching methods, students are able to gain a more comprehensive and systematic understanding of the impact of noise on architectural design, improving their ability to solve environmental issues and laying the foundation for future sustainable and intelligent building designs. This innovation in teaching methods will inject new vitality into architectural education and promote further development in the architectural design industry, particularly in terms of environmental protection and human-centered care.

3. Environmental Noise Monitoring Experimental Teaching

3.1. Teaching Objectives

The goal is to help students deeply understand the relationship between noise sources and environmental factors, while developing their observation and analytical skills. Students can start by identifying major noise sources on campus, such as traffic, industrial activities, and crowd gatherings, while also considering how noise propagates in different environments, like open spaces versus enclosed areas. This analysis enables a deeper understanding of noise impact on the built environment.

During field measurements, students are encouraged to consider multiple perspectives, including but not limited to locations such as the boundary of the campus where it meets urban roads, and teaching buildings or dormitories near busy city streets. These areas may face substantial traffic or industrial noise, particularly during peak hours in the morning or evening. Allowing students to select their own measurement points helps them develop skills in choosing appropriate locations for measurements, avoiding blind spots, and considering how noise levels may vary at different times of day.

When using a sound level meter, students need to understand the basic principles of noise measurement, including how sound pressure levels (dB) are calculated and how to operate the sound level meter. By measuring noise at different locations, students can compare the noise levels across various points and analyze the noise distribution patterns through data analysis. This activity not only helps students master the techniques for noise data collection but also cultivates their ability to conduct systematic analysis, preparing them for future simulation modeling exercises.

3.2. Selection of Experimental Scope

In this experiment, the Wuhan University of Engineering (Wuchang Campus) (see Fig. 1) is selected as the experimental measurement area. Located in the center of Wuhan, the university has heavy traffic both within and around the campus, with a complex surrounding built environment, making it ideal for noise monitoring and analysis. Choosing this specific area not only helps students better understand the characteristics of noise propagation in different environments but also enhances their ability to identify and perceive real-world noise sources.

At the beginning of the experiment, a classroom discussion was guide students to share their understanding of noise sources based on their daily experiences and perceptions. This session aims to help students start from subjective experiences to understand the impact of noise in various environments. For example, students may mention traffic noise around classrooms, air conditioning noise inside teaching buildings, or noise from sports activities on the playground. These discussions provided initial directions for selecting subsequent monitoring points.

Based on students' feedback and perceptions, several representative monitoring points within the campus were selected for the experiment (Table 1). The selection of these points takes into account the diversity of noise sources while ensuring the comprehensiveness of the experiment. The selected points include, but are not limited to, the following environmental types:

1) Around teaching buildings: For example, areas near city roads. The main noise source in these areas comes from road traffic, and students can measure the intensity of traffic noise using sound level meters.
2) Physical barriers: These points are chosen to help students understand the characteristics of low-noise environments.
3) Student dormitories: Students are most sensitive to noise when resting.

During the selection of monitoring points, students use sound level meters and other common acoustic instruments for field measurements, converting their subjective perceptions of noise into objective, quantitative data. This process is an important practical exercise for students to understand the impact of noise on the environment and helps them develop their skills in using acoustic equipment. By regularly recording noise levels (such as A-weighted sound pressure levels) and conducting spectral analysis of the noise, students gradually grasp the basic characteristics and propagation patterns of noise.

Furthermore, the experiment involves the analysis and comparison of measurement data. Students not only need to understand the distribution of noise sources but also analyze how noise affects campus life through data analysis. For example, they can compare the differences in noise levels between various monitoring points to analyze the noise level differences between busy traffic areas and quiet zones, as well as the changes in noise pollution across different times of the day.

Through this practical exercise, students do not only perceive and understand noise in real environments but also transform these subjective insights into actionable, scientific engineering data. This helps cultivate their practical skills and sensitivity, which is valuable for future work in architectural acoustics design or noise control.

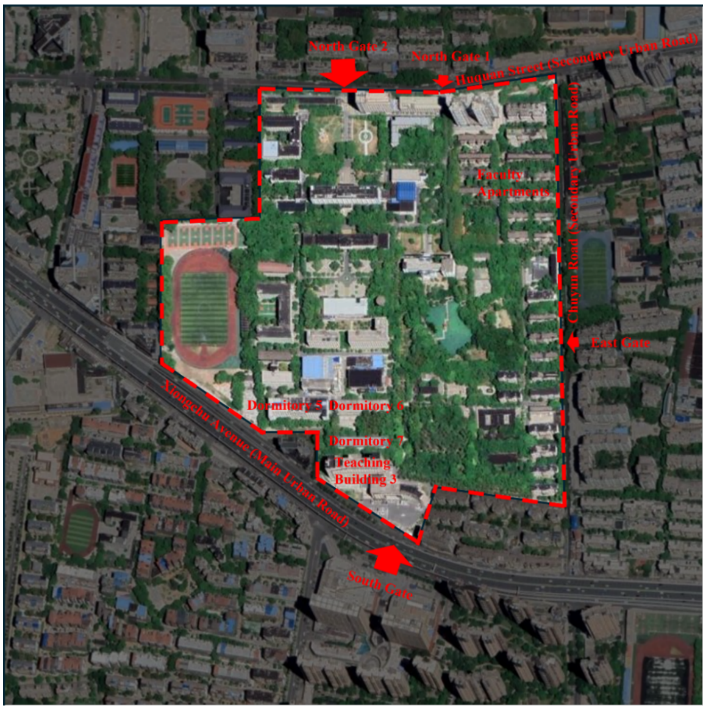


Figure 1 l Wuhan University of Engineering (Wuchang Campus)

Table 1| Description of Preset Measurement Locations

Measurement Location	Feature	Primary Noise Source	Other Preset Noise Sources
1-2	North boundary of the campus, adjacent to a secondary urban road	Traffic noise	Pedestrian noise
2-3	East boundary of the campus, adjacent to an urban secondary road	Traffic noise	Pedestrian noise, student play noise
3-4	South boundary of the campus, adjacent to a main urban road	Traffic noise	Pedestrian noise
A	North gate of the campus, varying building heights	Traffic noise	Pedestrian noise
B	East boundary of the campus, inside a physical barrier wall	Traffic noise	Pedestrian noise, student play noise
C	South boundary of the campus, 3rd teaching building at different heights (controlling open vs. closed windows)	Traffic noise	-
D	South boundary of the campus, 5th dormitory building at different heights (controlling open vs. closed windows)	Traffic noise	Pedestrian noise, student play noise
Random	Selected by students based on actual measurements, for comparative experiments	Student defined	Student defined

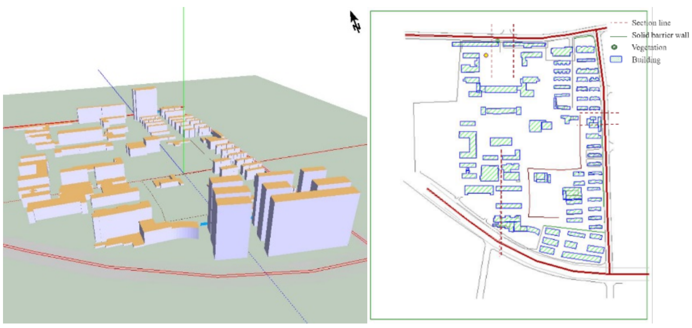


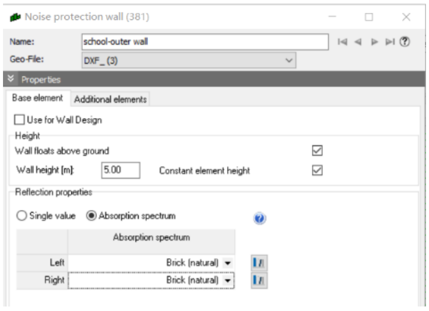
Figure 2 | Modeling of Wuhan University of Engineering (Wuchang Campus)

4. Simulation-Based Teaching With Environmental Noise Monitoring Data

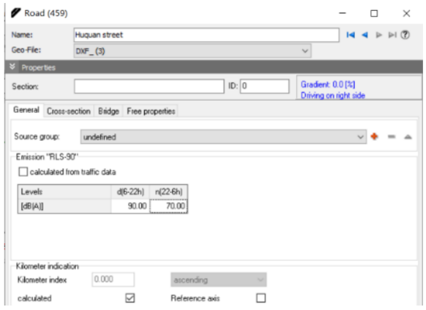
Students are introduced to advanced acoustic simulation technologies, gaining a deeper understanding of the complexity of architectural acoustic design. By using the SoundPLAN 8.2 acoustic simulation software to model the campus (see Fig. 2), students are able to convert actual measurement data into simulation parameters and import them into the model database. This allows them to simulate noise propagation and visualize the impact of different design solutions on noise levels. This process helps students integrate theory with practice, enabling more accurate calculations and predictions for noise control.

Teaching students how to input actual measurement data into simulation software (see Fig. 3) helps them understand the importance of each input parameter, such as noise source location, surrounding buildings, meteorological conditions, and more. Students must carefully input every parameter to ensure data accuracy, as even a small error could lead to deviations in the simulation results, which in turn could impact subsequent design decisions. Therefore, it is crucial to cultivate a rigorous experimental attitude in students, especially in architectural design, where overlooking details can lead to serious noise-related issues.

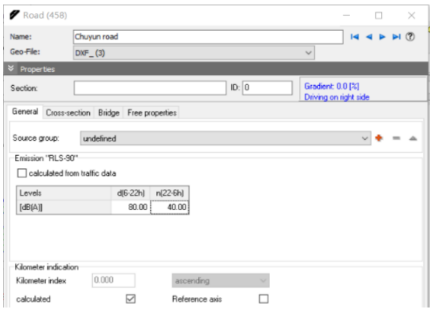
By displaying the simulation results, students will be able to observe the noise propagation paths, the noise level distribution across different areas, and the impact of building design on noise control. The simulation not only enhances students' technical skills but also strengthens their spatial thinking, helping them to more intuitively understand the relationship between architectural design and environmental factors.



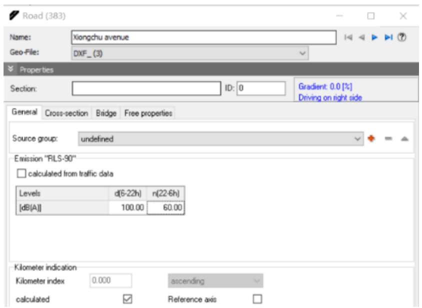
a) Parameters for the perimeter wall (also serving as a noise barrier) along the campus exterior on the urban road: Wall height is 5 meters, and the material is brick.



b) Noise parameters and road width settings interface for Huxian Street



c) Noise parameters and road width settings interface for Chuyun Road



d) Noise parameters and road width settings interface for Xiongchu Avenue

Figure 3 | Traffic Noise Source Parameter Settings

5. Teaching Design Strategies Based on Simulation Results

Based on the measurement data and simulation results, students will be required to propose specific noise control strategies. This process helps them apply the knowledge they have learned to real-world architectural design, thereby enhancing their design thinking and problem-solving abilities.

5.1. Planning Stage

During the site planning phase, students need to analyze areas within the campus that experience higher levels of noise (such as those near urban roads or busy traffic intersections) and reasonably lay out the functional areas of the building according to the noise distribution. For example, spaces that require quiet environments, such as dormitories and classrooms, should be located away from areas with higher noise levels to minimize the disturbance caused by noise.

The southern boundary, which is not shielded by any buildings, is directly exposed to external traffic sources (such as main roads), allowing noise to easily propagate along the southern edge and enter the campus. Due to the lack of effective sound barriers or building shielding, this side becomes a major source of noise. The sound waves travel directly into the campus, and especially low-frequency noise, which is not easily absorbed or attenuated by obstacles in the air, leads to significant noise disturbance. On the northern boundary, the presence of single-story and high-rise buildings reduces the impact of noise. In particular, the high-rise buildings, due to their greater height, provide a better sound barrier effect, effectively blocking external noise. High-rise building facades act as reflectors that can reflect or redistribute noise to surrounding areas, reducing the likelihood of noise entering the interior of the campus. However, noise intrusion at the northern gate remains relatively strong, likely due to the insufficient building shielding in that area, allowing noise to directly propagate into the region. To the east, the presence of solid walls provides relatively good sound insulation. Although the eastern boundary is near a city service road with lower traffic noise, the wall effectively limits the propagation of sound waves, keeping the noise disturbance in this area relatively low. The solid wall acts similarly to a sound barrier by increasing the path of sound propagation and energy loss, reducing the noise intrusion into the campus. In the northeast and southeast corners of the campus, near the road intersections, high-rise residential buildings serve as effective noise shields. These buildings reduce the propagation of traffic noise, especially in terms of low-frequency noise isolation, playing a crucial role in blocking unwanted sound. In architectural acoustics, high-rise residential buildings not only act as physical barriers but also alter the sound wave propagation path, reducing direct noise intrusion. The eastern part of the campus, primarily housing the faculty apartments, is relatively quiet according to simulation results. This area experiences lower noise levels due to the effective barriers provided by multi-story buildings and solid walls (see Fig. 5-a and 5-b). Additionally, the eastern area is far from the main roads and busy streets, which further helps in avoiding external noise interference. In contrast, the noise disturbance in the southern areas, such as in Teaching Building 3 (see Fig. 5-c) and Student Dormitory 5, is more significant. The noise is especially pronounced on the eastern side of Dormitory 5, where Dormitory 6 also experiences considerable noise impact. This is likely due to these buildings being located near noise sources (such as major roads or transportation hubs) and lacking adequate shielding or sound barriers. To improve noise isolation in these areas, acoustic barriers could be added, or the building facades could undergo soundproofing modifications (such as using sound-absorbing materials or thickening the walls) to reduce the intrusion of external noise.

Through this simulation analysis, it can be concluded that building design plays a crucial role in noise control within the campus. High-rise buildings and solid walls are effective in reducing the transmission of external noise, while low-rise buildings and areas lacking shielding are more susceptible to noise interference. For the southern boundary, the campus needs to consider adding noise barriers or taking other architectural acoustic measures to mitigate the impact of traffic noise. Additionally, for areas with more concentrated noise around the northern gate and the southern side, acoustic optimization designs could be considered, such as adding green belts, noise barriers, or sound-absorbing materials, to further reduce noise interference and improve the acoustic environment within the campus. It is also advisable to place buildings that require a quiet envi-

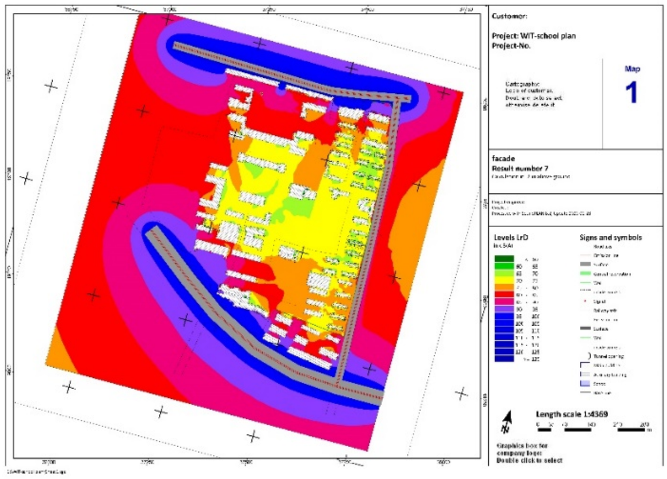
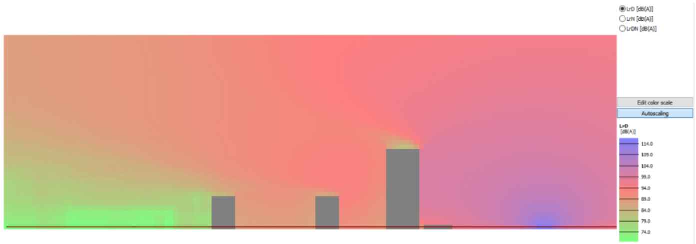


Figure 4 | Simulation Results for the Entire Campus (Affected by Traffic Noise)

a) Cross-sectional simulation results for the eastern boundary (with solid walls)

b) Cross-sectional simulation results for the eastern boundary (with solid walls and multi-story buildings parallel to the street)



c) Cross-sectional simulation results for the southern boundary (Right 1: High-rise building is Teaching Building 3; Right 2: Student Dormitory 7; Left 1: Student Dormitory 6; no solid wall)

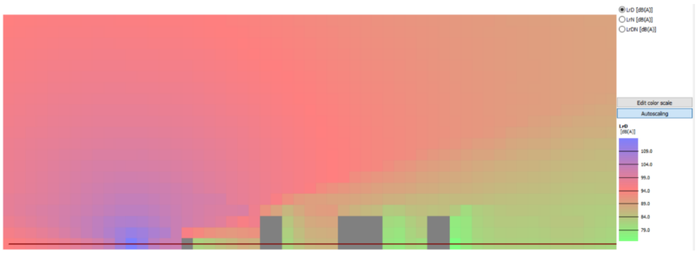
Figure 5 | Simulation Results for the Entire Campus (Affected by Traffic Noise)

ronment in areas further away from urban roads and busy streets.

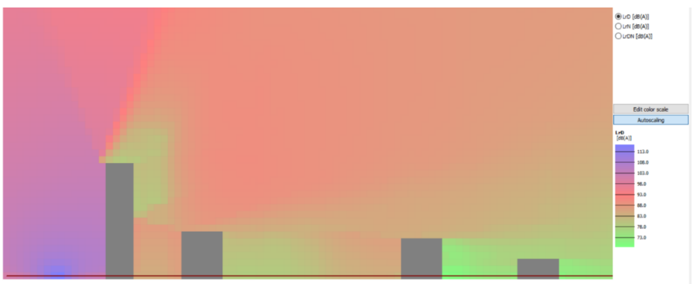
5.2. Design Stage

During the architectural design phase, students can propose noise control measures such as the use of soundproof materials and noise barriers. By modifying the design of the building's façade, improving the acoustic performance of windows, and refining the construction of the building envelope, the impact of external noise on the interior environment can be effectively reduced. At the same time, considering the building's external environment and surrounding traffic flow, the design of the building façade can be optimized through specific structural approaches to enhance noise reflection and absorption.

When analyzing the northern boundary of the campus (Fig. 6), the design of high-rise buildings offers significant acoustic advantages. The height of a building directly impacts its noise shielding effect. High-rise buildings typically increase the reflection path of noise, reducing the likelihood of noise transmission into the building. This is because the noise barrier effect of a building strengthens as its height increases, and the façade of a high-rise building can effectively block external noise sources, such as traffic noise. Acoustically, building height not only affects the propagation path of sound waves but also alters the pattern of sound wave distribution in space. Particularly in controlling low-frequency noise, high-rise buildings can effectively reduce the angle of incidence of noise by increasing the propagation distance and angle of sound waves, thereby mitigating the impact of noise on the building. In this scenario, the long sides of the buildings are oriented towards and parallel to the street.



a) Northern campus boundary (single-story building facing the street)



b) Northern campus boundary (high-rise building facing the street)

Fig. 6. Simulation cross-sectional results of the northern campus boundary (affected by traffic noise)

By using the building façade as a reflector, sound waves are reflected or dispersed to other areas, preventing noise from directly entering the interior of the building. Through this method, the building serves as a sound barrier in architectural acoustics, effectively blocking the impact of external traffic noise on the campus. In contrast, for single-story buildings, the relatively low height limits the reflection effect. The short façade of a single-story building cannot effectively reflect sound waves, and the intensity of reflected sound waves is weak. Furthermore, the sound barrier effect of a single-story building is insufficient to provide effective noise isolation. The reflection coefficient and soundproofing performance are generally strongly associated with the building's height and shape. Low-rise single-story buildings are less effective at reflecting high-intensity traffic noise, allowing noise to easily enter the building site.

As a result, students can clearly observe that high-rise buildings offer significant advantages in architectural acoustic design for noise control. By adjusting the building's height, shape, and material selection, noise can be effectively reflected, refracted, and absorbed. In contrast, single-story buildings, when facing external noise, require additional acoustic design measures to compensate for their limited soundproofing performance.

5.3. Renovation Stage

During the renovation phase, students can propose noise control measures for existing buildings on campus. Taking the street-facing sides of Building 3 (teaching building) and Buildings 5 and 6 (student dormitories) on the southern boundary as examples, noise interference inside the buildings can be reduced by adding window soundproof layers and double-glazed curtain walls. Additionally, adjustments to the external environment, such as the permeability of campus walls and vegetation types, can be explored to improve the acoustic environment through natural noise barriers.

6. Discussion and Conclusion

Due to factors such as wind speed, air humidity, and the varying sound absorption characteristics of different environmental elements (such as buildings and vegetation), the simulation results often show certain discrepancies with the measured data. This phenomenon helps cultivate students' ability to analyze and identify the acoustic characteristics of the environment and encourages them to apply these characteristics in practical planning and design.

At the current stage, teaching primarily relies on field measurements, aiming to equip students with the skills to operate common acoustic instruments, such as sound level meters, while also enhancing their awareness of the impact of noise in design. However, students in this process typically only have access to raw numerical data and tables, which may leave them at a theoretical level. To address this limitation, combining simulation results with field measurement data in a visual format allows students to more intuitively understand the path of noise propagation. This approach not only stimulates students' interest but also helps them build a more solid acoustic knowledge system, which provides greater depth compared to mere theoretical learning and data tables. Through this integration, students will be better equipped to accurately identify noise sources, assess noise impacts, and consider noise issues comprehensively based on both subjective and objective standards in their future work. This process will assist them in applying architectural acoustics principles more effectively in building design and site planning, thereby improving the environmental adaptability and comfort of their designs.

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The Application of Digital Twin for Indoor Air Quality Management: a Case Study in Hong Kong

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Indoor Air Quality (IAQ) Control,
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ABSTRACT

With the advocacy of the development of smart cities, buildings are also evolving to become smarter and more user-friendly. Employing cyber-physical technologies, such as the Internet of Things (IoT), Digital Twin (DT) and Building Information Modeling (BIM), can effectively monitor and control the built environment. DT is an emerging tool that connects the building to its digital replica so that the building's situation can be monitored and presented to users effectively. This paper proposes a DT framework for building management to discover the applications of DT for indoor environment monitoring and control. A case study of a DT-driven indoor air quality (IAQ) system is completed to demonstrate the implementation of DT in the built environment. The system demonstrated the key features of DT, including monitoring, simulation, control and prediction, and showed their roles and functions in IAQ management. Finally, the difficulties and limitations, i.e. sensor selection and installation, of implementing the DT system in the built environment are presented after the case study.

1. Introduction

In the digital age, smart cities and buildings are highly pursued to improve living quality and environmental sustainability. To be a modern and smart building, the situations inside the building should be measured, monitored and displayed remotely, and then the data can be used to prognosis and enhance the building's performance in the future [1, 2]. However, the environmental and indoor conditions are difficult to present accurately and in real-time to users due to the communication delay between far distances and rapid change of conditions. The appearance of digital twins (DT) fills the technical gap between the physical environment and its digital model in that the data of the real environment can be instantly shown in the digital replica through the computer or mobile devices, i.e. smartphone and tablet. DT can be an immense technology for building management, maintenance planning, and improving decision-making in equipment selection for building design or repair [3-5].

The concept of DT was initially proposed by M. Grieves in 2002, using data to link up the physical

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and virtual space for product lifecycle management [6]. NASA first used "Digital Twin" in 2010 on their technology area roadmap report [7]. Then, DT is universally accepted to represent the twinning technology between the physical object and its digital model. DT is widely applied in manufacturing and aerospace for process monitoring, failure prediction and supporting decision-making [5, 6]. DT-related research has been pursued in recent years, and its application has been extended to different areas. Building and construction are among the leading areas in DT study [8]. DT and other enabling technologies, e.g. Building Information Modeling (BIM), Cloud Computing and Artificial Intelligence (AI), can drive the whole building lifecycle to be visible, predictable and controllable [2, 9, 10]. As the construction industry continues to evolve, companies should embrace these technologies to remain competitive, meet the demands of a rapidly changing market and construct more efficiently with higher quality [11].

Monitoring and control are the common applications of DT in building management. To achieve a more user-friendly and smart building environment, different types of sensors can be installed to collect the environmental data, e.g. temperature, humidity and concentration of different pollutants in the indoor area, and use those data to analyse and predict the maintenance plan. Nowadays, people spend 90% of their time indoors, i.e., in schools, offices, factories, and residences [12]. Indoor Air Quality (IAQ) is one of the important environmental factors in indoor environment management that directly affects the user's comfort, decreasing operating performance and causing different health problems, i.e. sick building syndrome (SBS) and building-related illness (BRI) [13, 14]. According to data from the World Health Organization in 2014, about 4.3 million people die annually from household air pollutants, including stroke, ischaemic, heart disease and chronic obstructive pulmonary disease [15]. Also, poor air quality and ventilation will raise the chances of death from COVID-19 infection [16]. Therefore, an integrated and smart IAQ monitoring and control system should be developed in modern buildings to monitor indoor pollutant levels [13], maintain air quality, warn users, and predict maintenance plans and schedules.

This paper presents the DT-based IAQ monitoring and control system in the Hong Kong Insitute of Vocation Education (IVE) and discusses the DT application in IAQ management. The rest of this paper is organised as follows: Section 2. presents the framework of DT in Smart Buildings for built environment management. Section 3. presents the DT-based IQA monitoring and control system in IVE. Section 4 discusses DT's limitations and potential applications in IAQ control or building management. Section 5. concludes the outcomes of this study.

2. Digital Twin Framework for Building Management

Digital Twin has three main elements: a physical object, a virtual model, and the connection that binds these two together [10], so developing a DT in a smart building is a huge-scope project. Therefore, the DT implementation in smart buildings can be divided into four levels, as shown in Figure 1. The product-level DT can represent the real-time situation of household products, e.g. Fan, Light and Air Conditioning. The data can be used to monitor the equipment's health, control it and predict maintenance [4]. The unit-level DT represents the connection between the physical world and its digital replica of a single room or unit. The unit's systems, environment, room conditions and equipment are considered and controlled. The building-level DT is integrated with all the unit DTs to represent the overall building's performance or system, e.g. power system, water supply system and ecosystem [17]. The co-relationship and interference between the units can be monitored, controlled and predicted the improvements that can more effectively manage the overall performance of the building. The city-level DT is the ultimate goal of developing a smart city that involves not only the building DTs in the city but also the product DTs, i.e., the traffic system, city power system, and urban planning [18]. The scope of work is very large, and the government or some leading enterprises usually initiate it. Therefore, most DT projects are constructed under product level, e.g. equipment DT [19], unit level, e.g. factory shop floor DT [20], and building level, e.g. Cambridge Campus DT [9].

The unit-level DT is the focus of this paper. A completed unit-level DT should include the related product DTs, e.g. air-conditioning, lighting and ventilation, that can affect the surrounding environment directly or indirectly. The unit environment DT and product DT should interact so the unit condition can instantly trigger the product reaction. In modern buildings, building service equipment is important in controlling the indoor environment, affecting users' comfort and improving resource management. The equipment's per-

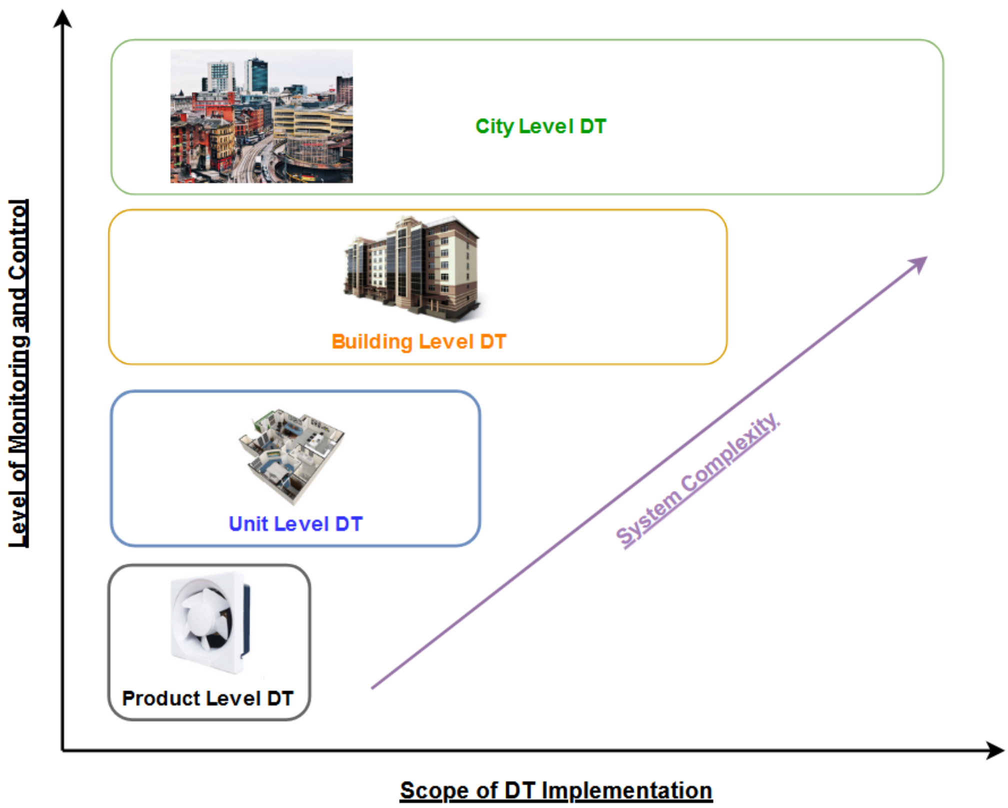

Figure 1 I DT Implementation Level in Smart Buildings

formance can be optimised, and sustainability can be improved by accurate real-time control and effective management [21]. Figure 2 shows the conceptual interaction framework between room DT and product DT. The product and the room's indoor environment interact in the physical world; for example, the air conditioning will operate to cool down the room, and it will be turned off if the environment is cool enough. The sensors installed in the environment and embedded in the product can measure the environment data, e.g. temperature, humidity and the number of users, and the product data, e.g. real-time status and operation schedule, and sync to the server. The virtual replicas of the room and products receive the measured data from the physical world and represent them in the virtual mode immediately. The data can be analysed and simulated in the digital model, and the results can be shared with the physical world and users. The results can support decision-making and control the products to provide corresponding reactions, e.g. turning off the fans and switching the A/C. All data, i.e. measurements, simulations and user actions, can be backed up on the cloud or local database and be used to support the decision-making and scheduling by machine learning, e.g. daily schedule of lighting on/off, predicting maintenance plan. Those data can be critical to achieving indoor environmental quality (IEQ) control, which can manage air quality, thermal environment, sound, and light and their effects on comfort and well-being [22].

The DT-based smart building has four main stages: monitoring, analysis, control and prediction. As shown in Figure 3, the physical environment and virtual replica contribute to each stage and interact. The physical environment is monitored, and the environmental data is recorded. Different sensors in the physical world also measure the product status and user actions. Those data would be analysed in the virtual replica to get the simulation and building information analysis results [21], e.g. energy consumption [23] and airflow analysis. Then, the server can use those results and data to make a suitable decision and action, e.g. send a signal to turn on the fans. The decisions made by data analysis, machine learning, and artificial intelligence in the digital world can give feedback on products and the physical environment. The products can be operated automatically to control the environment and give users feedback via apps or product features, e.g., Buzzer, LED or Vibration Motor. The users can also manually control the products or adjust the control parameters to suit specific needs or preferences. All data, information, and

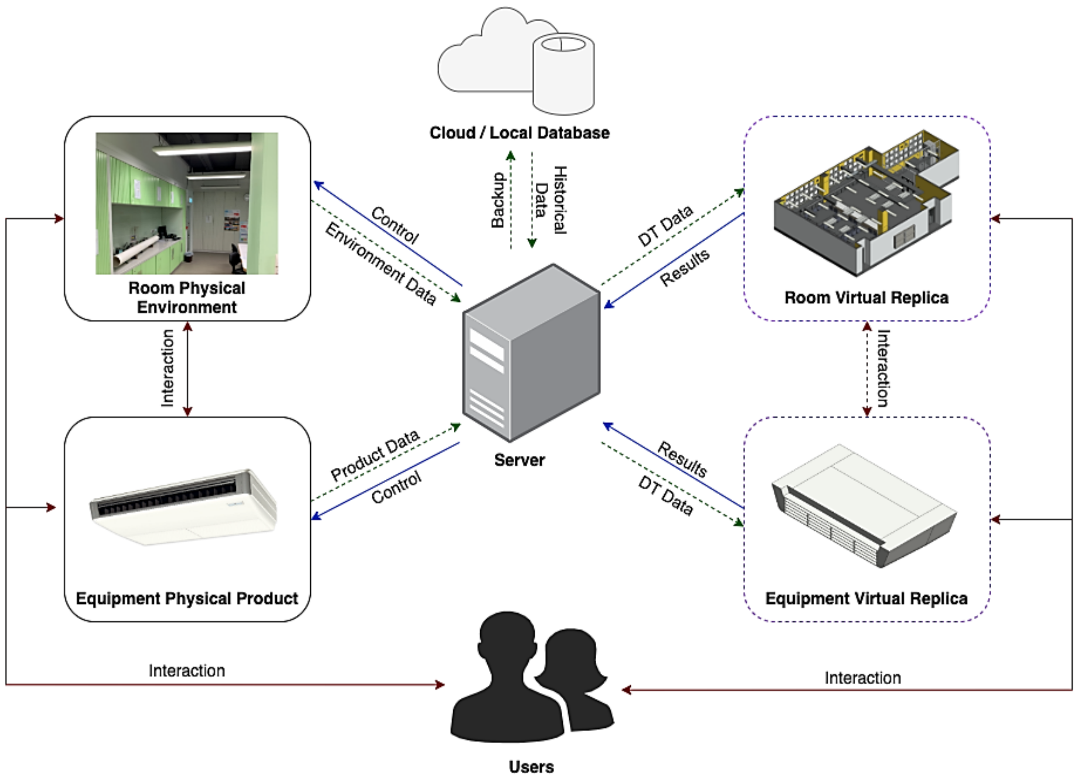

Figure 2 I The conceptual framework of DT-based unit management

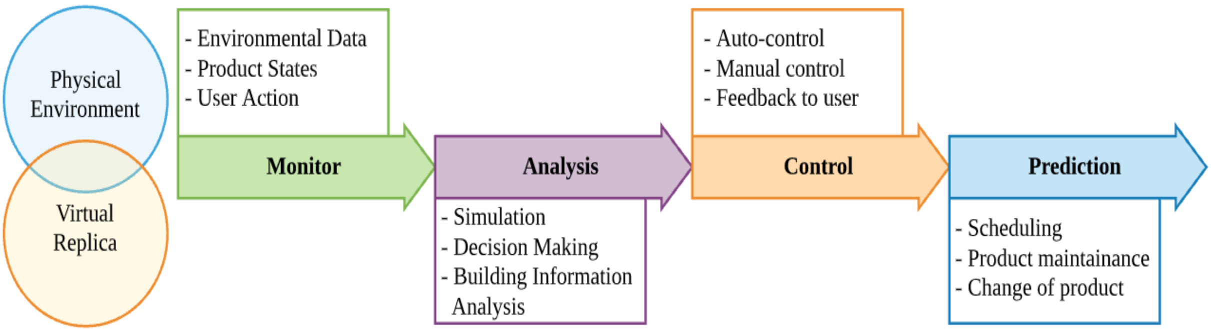

Figure 3 I Data Flow of DT system for smart building

actions performed at each stage are stored in the cloud database, creating a comprehensive record of operational history. This data can be analyzed and used to predict future situations and recommend corresponding actions, such as optimizing lighting schedules or creating proactive product maintenance plans. Additionally, the historical data is highly valuable for engineers, as it enables them to evaluate product performance over time and select the most suitable replacements for aging or outdated products. This approach not only helps optimize user satisfaction but also promotes sustainable design practices by ensuring efficient resource usage and minimizing environmental impact. The conceptual framework and flow are detailed in Figure 3.

3. A Case Study of DT-Based IAQ Control in Hong Kong Institute of Vocation Education (IVE)

The Hong Kong Institute of Vocational Education (IVE) of the Vocational Training Council developed a Digital Twin (DT) system for a laboratory at its Tuen Mun campus. This represents a significant advancement in smart facility management and interactive learning environments. The project involved the installation of multiple types of sensors, including current probes, lumen sensors, indoor air quality (IQA) sensors, and contact sensors, to capture a wide range of environmental and operational data. These sensors continuously monitor energy consumption, lighting levels, air quality, and room occupancy status

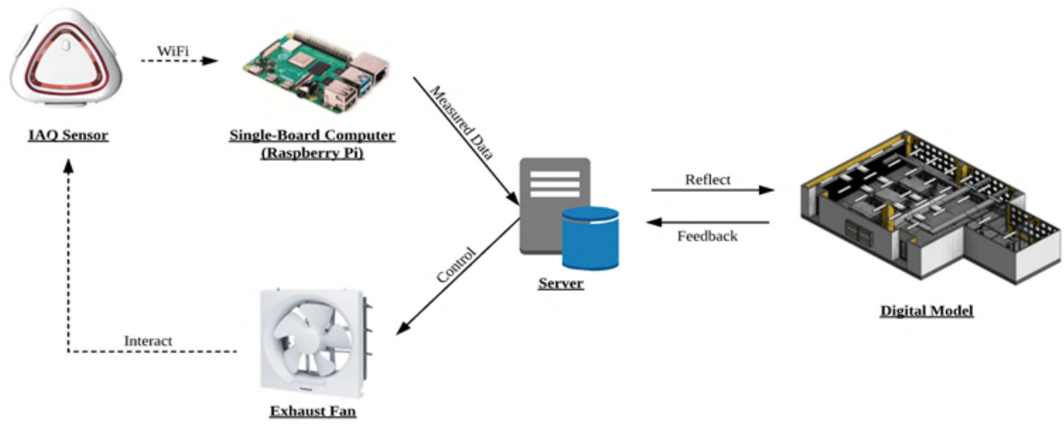

Figure 4 l Configuration of DT-based IAQ monitoring and control system

to provide a comprehensive, real-time understanding of the laboratory's conditions. The data collected from these sensors is synchronised with the laboratory's Building Information Modeling (BIM) system, creating a dynamic, virtual representation of the physical space. This sensor data integration with the BIM model allows the DT system to display real-time and historical information about the laboratory's environment and operations. The synchronised data is accessible through a web-based browser interface, enabling users to interact with the DT system through PCs, smartphones, or other smart devices.

This system supports various user groups, including students, laboratory assistants, and faculty managers, by providing instant access to the laboratory's operational data. The DT system offers students an interactive platform to learn about smart building technologies and data-driven decision-making. Laboratory assistants can utilise the system to monitor equipment usage, optimise resource management, and ensure safety compliance. Faculty managers benefit from the ability to oversee multiple laboratories remotely, analyse energy usage patterns, and identify areas for operational improvement.

This case study focuses on DT-based IAQ monitoring and control, and other possible applications are discussed in Figure 4. The configuration of the DT-based IAQ monitoring and control system is shown in Figure 4. The IAQ sensors measure the air pollutant level in the room, and the data will be sent to a single-board computer via WiFi. The measured data are synced to the server and reflected on the digital model. The digital model can present the data clearly to the user, and they can control the exhaust fan on the system. The system will analyse the measured data and feedback to the server, then automatically control

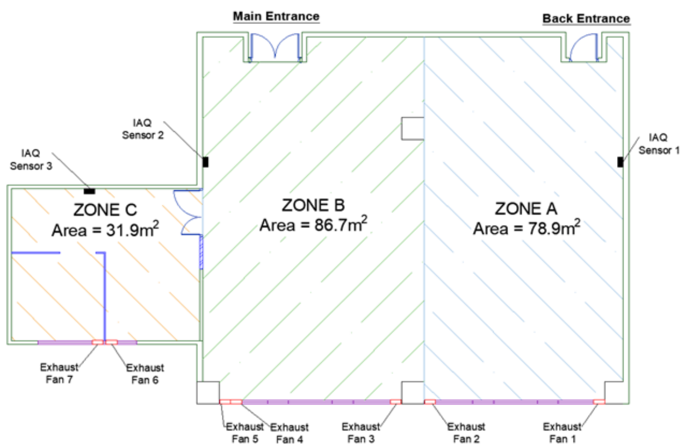

Figure 5 l Arrangement of IAQ sensors and exhaust fans

the exhaust fans. When the exhaust fans are on, indoor air pollutants can be exhausted out of the areas. The operation of exhaust fans can interact with the sensors and develop a closed-loop monitoring and control system.

The laboratory can be divided into three main areas, and the location of the IAQ sensors and exhaust fans are shown in Figure 5. The IAQ sensor 1 is decided to monitor the IAQ in Zone A and control exhaust fan operations 1 and 2. And then sensor 2 is located in Zone B and controls exhaust fans 3, 4 and 5. Finally, sensor 3, located in Zone C, controls exhaust fans 6 and 7. The mechanism and operation of the system will be monitored in the next section.

3.1. DT-Based IAQ Monitor and Control

IAQ is an important factor in indoor environment quality as it can cause building-related illness to the users, e.g. cough and chest tightness [24]. Therefore, it is necessary to develop a smart IAQ control system

Figure 6 I User Interface of DT-based IAQ Monitoring and Control System

in the indoor environment, especially in schools, offices, and hospitals, which are densely populated. The case of DT-based IAQ monitoring and control systems in IVE is presented stage by stage, as mentioned in Section 2: monitoring, data analysis, control, and prediction. The IAQ sensors used in this case can measure the surrounding temperature, humidity, concentration of carbon dioxide (CO2), total volatile organic compounds (TVOC), PM10 and PM2.5, which are the common factors to indicate IAQ. According to the guideline of the IAQ certification scheme for office and public places (2019) issued by the Hong Kong Environmental Protection Department (EPD) [25] and the standard of ventilation for Acceptable Indoor Air Quality issued by ASHRAE [26], the target values of those pollutants are listed in Table 1. The selected pollutants should be controlled within the target values at any time.

3.1.1. Monitoring

The sensors monitor and record the concentration of selected pollutants, such as carbon dioxide (CO2), particulate matter (PM2.5 and PM10), humidity, and volatile organic compounds (VOCs), across different areas of the room. As shown in Figure 6, the system displays real-time indoor air quality (IAQ) data for each pollutant in every monitored space area. This detailed visualisation enables users to assess environmental conditions quickly and accurately. Numerical data values are presented alongside visual indicators, making it easier for users, such as students, faculty managers, or laboratory personnel, to understand the pollutant levels in specific areas and identify zones that require attention.

Faculty managers or health officers can remotely access the system via the internet to monitor the real-time IAQ situation at any time. This accessibility allows them to take immediate action when pollutant concentrations exceed acceptable thresholds. Actions may include scheduling air filter cleaning, enhancing

Table 1 I Target values of the selected IAQ pollutants [25] & [26]

IAQ Pollutant	Unit	Target Values
Carbon Dioxide (CO2)	ppm	<1000
Respirable Suspended Particulates (PM10)	ug/m	<100
Total Volatile Organic Compounds (TVOC)	ppb	<261

ventilation, or reducing the number of room occupants to improve air quality. Such proactive interventions ensure a healthier and safer environment for all room users. The BIM model of the room is stored securely in the cloud and integrated into a cloud-based platform using Autodesk Fusion 360. This platform allows users to access and interact with the system on various devices, such as PCs, tablets, or smartphones, ensuring a seamless and user-friendly monitoring experience.

3.1.2. Data Analysis and Simulation

The measured data can be represented in the digital model in real-time, enabling immediate analysis and visualization. This data can be utilized to simulate the physical environment, such as airflow and air change rates, using Computational Fluid Dynamics (CFD) technology to identify the causes or sources of pollutants [27, 28]. These simulations provide actionable insights for improving indoor air quality (IAQ), such as recommending the opening of specific windows to enhance ventilation. The data also supports automated decision-making processes. As shown in Figure 7, the exhaust fan control logic is programmed to turn on or off based on IAQ changes. Additionally, the simulation results are valuable for future design or renovation projects, helping to optimize the arrangement and location of equipment, such as determining the ideal height for inlet and outlet openings [28], ultimately enhancing the room's overall performance and efficiency.

3.1.3. Control

Once the decision is made, the server can send a signal to the programmable logic controller (PLC) to activate or deactivate the relay of the exhaust fans. This allows for automated control of ventilation based on real-time indoor air quality (IAQ) data. Users have the flexibility to set target pollutant values and customize the delay time for turning off the exhaust fans, ensuring efficient operation tailored to specific needs. By reviewing the data and simulated results on the virtual model, users can also manually control the exhaust fans, switching them on or off to actively reduce pollutant levels in the room as needed.

Beyond controlling the exhaust fans, the collected data can trigger a variety of automated actions within the built environment. These include turning on or off lights, adjusting curtains to optimize natural lighting, and managing other resources such as HVAC sys-

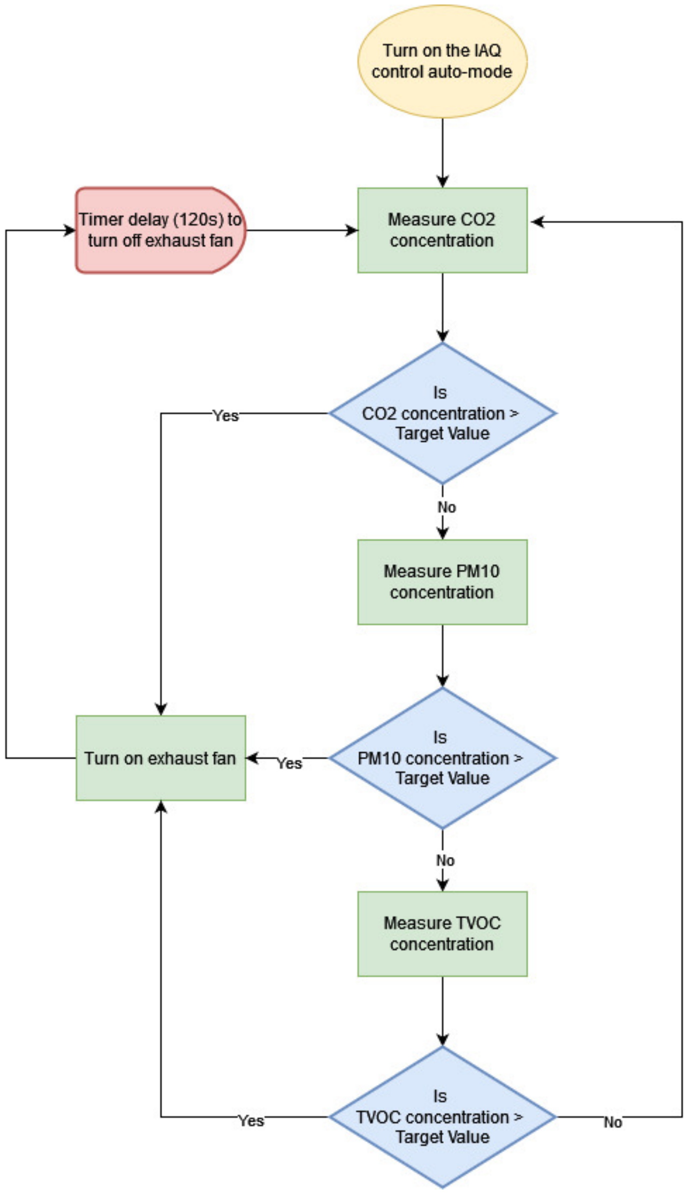

Figure 7 | The logic flow of the IAQ control system

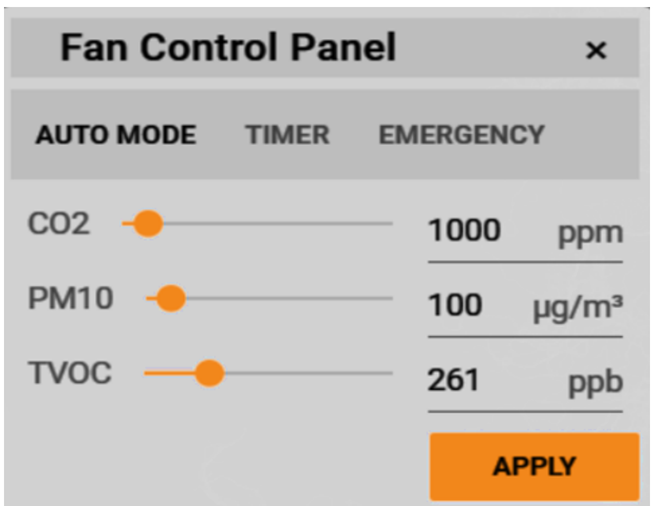

Figure 8 | Fan Control Panel for target value setting of each pollutant

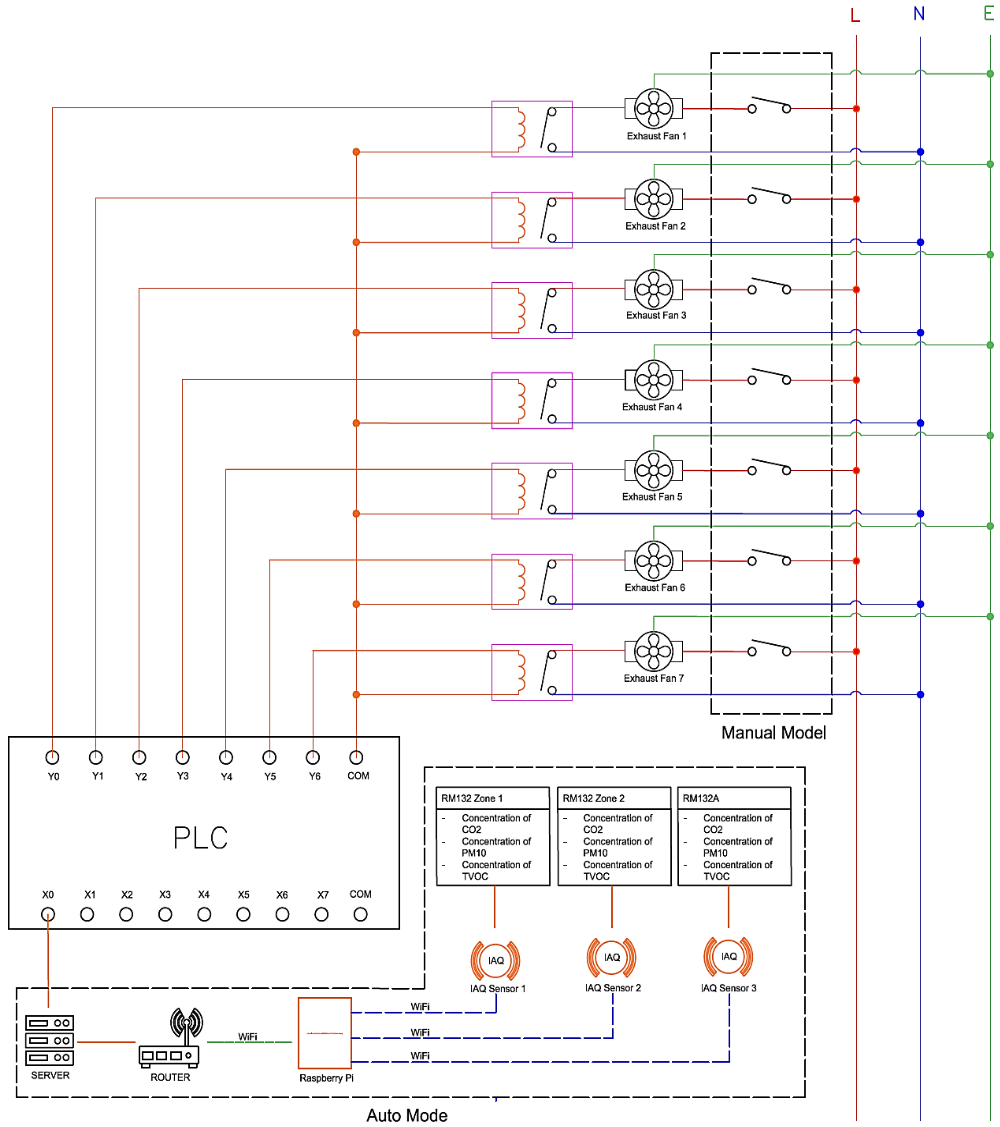

Figure 9 I Schematics of exhaust fan control

tems. By integrating these controls, the system enhances operational efficiency, optimizes resource usage, and improves occupant comfort. This approach demonstrates how Digital Twin (DT) technology can provide a comprehensive framework for automating and managing multiple systems in a smart and sustainable manner, further showcasing its value in modern building operations and environmental control.

3.1.4. Prediction

Finally, all the data, room information, and user records are synced and securely stored on the server, creating a comprehensive database for analysis and decision-making. The measured data can be analyzed using AI to predict trends in indoor air quality (IAQ) changes. These predictions can improve exhaust fan operation planning by allowing proactive measures, such as turning on the fans in advance before peak hours to maintain optimal air quality. Additionally, the operational hours of each exhaust fan can be tracked to predict maintenance schedules or estimate the lifespan of the equipment [19]. This predictive approach ensures timely maintenance, reduces downtime, and extends the life of building systems.

The predictive insights not only enhance building environment optimization but also improve operational decision-making [3]. Relevant stakeholders, such as building service engineers and faculty managers, can access historical data, simulations, and analysis results to redesign or upgrade the room. These insights can guide device selection, equipment specifications, and system improvements, ensuring the room is better equipped to meet future demands. This integrated system of data-driven predictions, in-

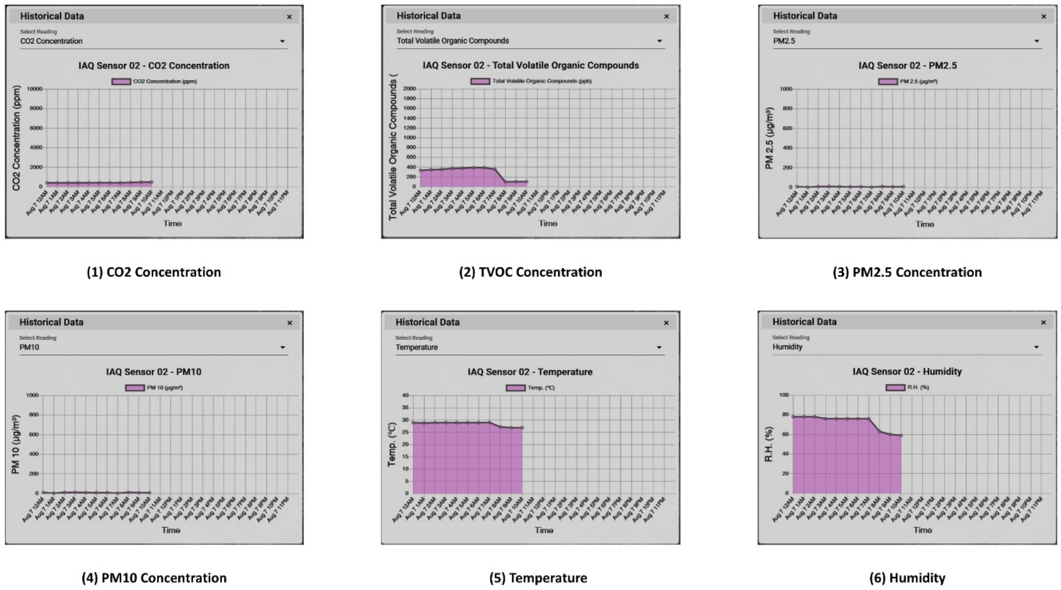

Figure 10 I Historical IAQ data of the room

formed decision-making, and proactive management highlights the value of leveraging advanced technologies for sustainable and efficient building operations.

4. Discussion

The DT project in IVE demonstrated the framework of DT-based IAQ monitoring and control. The real-time data monitoring feature allows the user to understand the invisible information, e.g. pollutant concentration, on the virtual model. The measured data can further simulate the indoor situation, support decision-making, control the related equipment and predict future trends. Using those analysis results and data, the engineer can generate a more accurate room design by choosing the suitable device and location to optimise building energy efficiency [4, 23] and improve the performance of future buildings [4]. Building Information Model (BIM) is an emerging technology for building design and management that benefits engineers and developers to create virtual environment replicas and perform simulations [17, 21, 29]. Integrating DT and BIM can optimise the whole building lifecycle.

The DT-based building monitoring and control system seems beneficial for building management, but some limitations are found when developing the project. According to the United States Environmental Protection Agency's definition [30], IAQ is affected by not only the gases (CO2 and TVOC) and particulates mentioned in the demonstration project in IVE but also other hazardous gases (e.g. Nitrogen Dioxide, Radon and Carbon Monoxide) and biological pollutants. Many kinds of pollutants can affect the IAQ, so a well-structured sensor network to detect those pollutants should be developed to measure and monitor the IAQ comprehensively. It is a great challenge to set up a complicated sensor network in the built and operating building because of the limited space and lack of appropriate locations for the sensor installation. In addition, extra effort and investments should be made in using buildings, for example, redesigning the system, creating digital models, and rearranging the room furniture and equipment. There are low incentives and efficiency in implementing and developing the DT system in the constructed and used buildings. To optimise the performance of the sensor network and DT system for indoor environment monitoring and control, IAQ, temperature, humidity and brightness should be designed and developed in the early stage of the building lifecycle. As shown in Figure 11, the difficulty of implementing DT in the building increases along with the building lifecycle due to the location restriction and interference with the other equipment and system. Implementing DT in the earliest stage of building development can gain the most benefits along the building lifecycle. DT can be implemented in the early stage of the project and integrated with other building technologies, i.e. Building Information Modeling (BIM), Internet of Things (IoT),

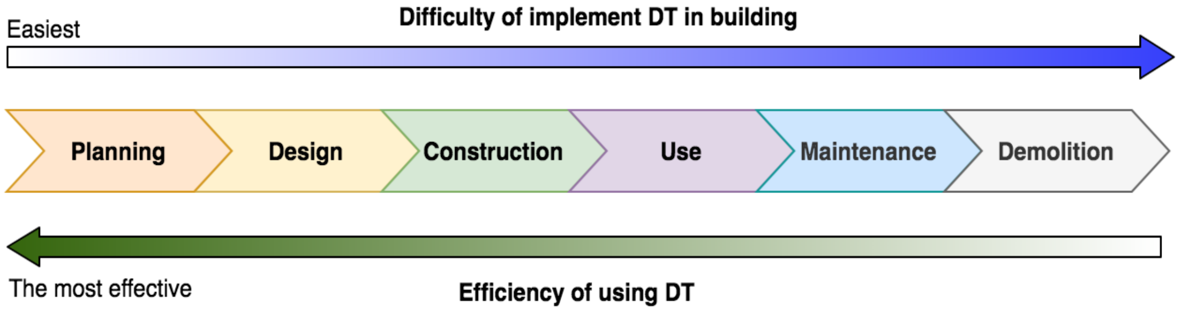

Figure 11 | Level of difficulty and efficiency to implement and use DT in the building lifecycle

and Geographical Information Systems (GIS), to maximise the use of DT [2]. Applying simulation to evaluate IAQ at the design stage can improve the IEQ, and DT can provide mass data to support the simulation. DT also has various applications in the whole building lifecycle, i.e. construction site logistic management, fault detection [10] and energy control [23]. Therefore, effectively implementing DT in the planning and design stage is an important topic for the industry.

In the future, there are some possible directions for DT in the building and construction industry. The study of implementing DT in the planning stage of the construction project can optimise the efficiency of the whole building lifecycle. The guidelines and framework for applying suitable sensors in planning and design can make DT easier to implement and maximise its usage. With the development of Modular Integrated Construction (MiC) technology, the sensors and DT system can be installed in the factory in advance so that the DT system can be used to optimise the construction processes, e.g. progress monitoring and quality control, and also be used when the building is completed. It is a fatal opportunity for the industry to merge and implement MiC, BIM and DT into future building design.

On the other hand, it is not easy to implement a comprehensive DT system at the time or by a single party. Different vendors can provide different equipment or systems in the building. Therefore, an integrated platform for connecting and coordinating different DT systems should be designed. For example, the air-conditional DT should be able to operate individually and also interact with the room DT to optimise the built environment control and management. The performance of the single DT is limited, so the integrated management platform can maximise the building's performance in the future.

5. Conclusion

The paper describes how using Digital Twin (DT) technology has significantly extended the application of Building Information Modeling (BIM) throughout the building lifecycle, encompassing planning, design, construction, and ongoing monitoring and control during building operation. DT bridges the gap between the physical and digital worlds by integrating real-time data with virtual models, enabling more efficient and effective building management. The study focuses on designing and implementing a DT control system for managing indoor air quality (IAQ) in a school laboratory in Hong Kong. It demonstrates DT's various roles and applications, including monitoring environmental conditions, analysing data patterns, simulating airflow and pollutant sources, and predicting future scenarios for proactive decision-making. The findings highlight how DT can effectively control and improve IAQ, thus enhancing building occupants' comfort, health, and performance.

The case study offers valuable insights into the broader applications of DT in the building industry, showcasing its potential to optimise building performance, streamline operations, and enhance sustainability. It also addresses the limitations and challenges of DT implementation, such as restricted installation spaces for sensors, high costs, and potential issues with system performance and data integration. The paper emphasises that the most effective way to implement DT is during the design stage of a construction project. This ensures seamless integration of DT technology, allowing for the full realisation of its benefits, such as improved energy efficiency, better resource utilisation, and more informed maintenance planning throughout the building's lifecycle.

Conflicts of Interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Assessment and Countermeasures of the Impact of Travel Patterns on Obesity Problems of Urban Residents

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KEYWORDS

Obesity,
Travel Patterns,
Urban Transportation,
GWR Model,
OLS Model

ABSTRACT

This study examines the relationship between travel modes and residents' obesity in Wuhan, using data from 93 streets. Travel modes (walking, cycling, public transit, and car travel) were analyzed alongside BMI as an indicator of obesity. Ordinary Least Squares (OLS) and Geographically Weighted Regression (GWR) models revealed the following: (1) Walking, cycling, and public transit distances were negatively correlated with obesity, with walking and cycling having stronger effects than public transit, while car travel showed a positive correlation. (2) Public transit station density was positively correlated with obesity and influenced the relationship between travel modes and obesity. Areas with higher station density showed stronger correlations with public transit and car travel distances, while lower station density areas emphasized walking and cycling. (3) Obesity levels varied significantly across regions. Further research is needed to validate these findings and explore the complex dynamics of urban travel and obesity.

1. Introduction

Obesity is the main cause of illness and premature death worldwide (Finkelstein et al., 2009; Friedenberg, 2002; Goldner, 1956), even considered as global epidemic and recognized as a multi-system public health issue (Su et al., 2017). Obesity increases the risk of various chronic diseases such as type 2 diabetes, hypertension, dyslipidemia, coronary heart disease, and certain types of cancer. As of 2010, it was estimated that overweight and obesity caused 3.4 million deaths globally, accounting for 3.9% of years of life lost and 3.8% of disability-adjusted life years. Due to established health risks and increased prevalence of obesity-related diseases, obesity has become a major global health concern. The World Health Organization has developed the "Global Action Plan for the Prevention and Control of Noncommunicable Diseases 2013-2020," which includes strategies to curb the rising global obesity rates and bring them back to the levels of 2010 ("Global NCD Action Plan | WHO FCTC," n.d.). Data shows that by 2023, the number of obese individuals in China has already exceeded 250 million. The proportion of overweight adults in China is approximately 20%-30%, and in large cities, due to improved living standards, this proportion has reached 35%-40%. There has been a

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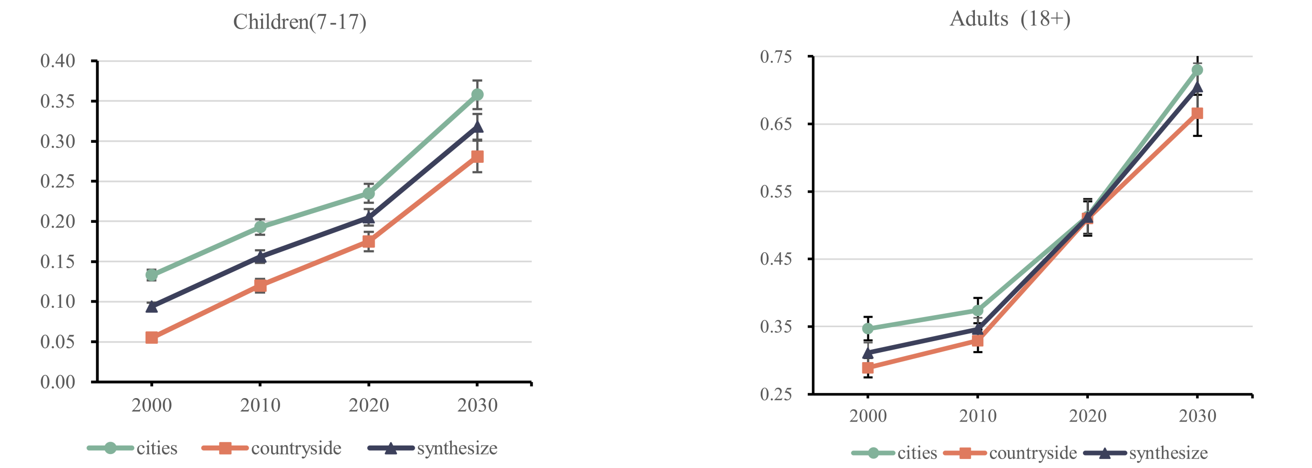

Figure 1 | Obesity rates by age (with projections)

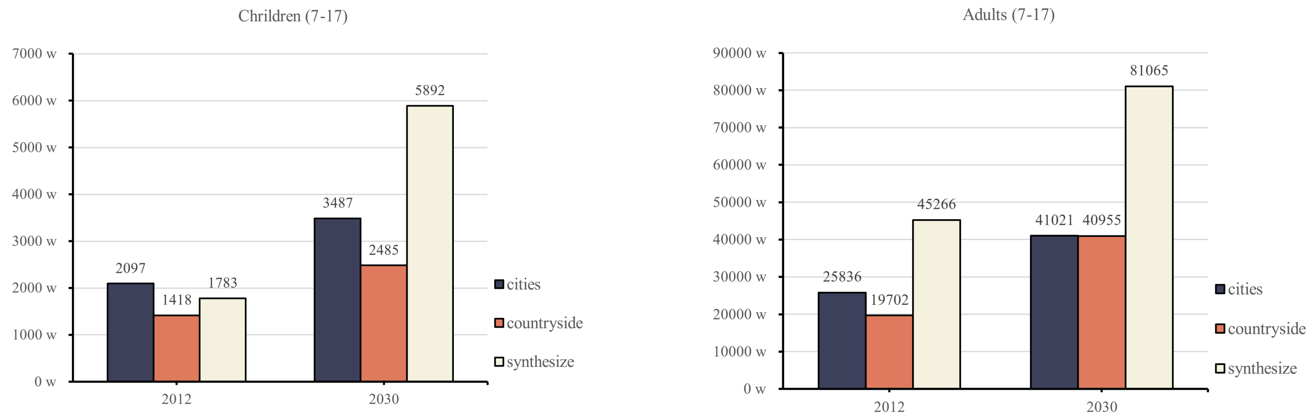

Figure 2 | Prevalence map of obese people in China (with projections)

surge in chronic diseases such as hypertension, fatty liver, diabetes, and cardiovascular diseases caused by obesity, making it an invisible killer of public health in China.

The following are predictions of obesity rates and incidence rates for residents of different age groups in rural and urban areas, as shown in Figure 1. It can be observed that patients with obesity account for a large proportion in both adult and children's populations, with urban residents having significantly higher obesity rates than rural residents, and the proportion of obese individuals is increasing year by year. Figure 2 shows the number of obese individuals in China with corresponding disease incidence, indicating that the disease incidence among urban obese individuals remains higher than that of rural areas, and it is expected to continue rising in the future. Therefore, it is worth studying and exploring prevention and control measures for the societal health issue of obesity. In this context, our team takes residents' daily commuting patterns as a starting point to study the relationship between commuting patterns and obesity issues, and based on this, propose relevant recommendations to provide a theoretical basis for the effective control of global obesity problems.

2. Literature Review

Researchers have conducted extensive studies on the factors influencing obesity. Foster et al. (2018) investigated the impact of transportation noise on obesity and metabolic disorders, finding that long-term exposure to road traffic noise increases the risk of obesity. Similarly, Mundorf et al. (2018) argued that targeted communication can encourage different population groups to adopt active and sustainable transportation modes, helping to mitigate rising obesity rates. An et al. (2020) reviewed evidence linking economic globalization to obesity, evaluating this relationship at the national level using longitudinal and cross-sectional research designs. Li Xin et al. (2022) examined the risk of ischemic heart disease, a major obesity-related condition, by analyzing multiple data sources in Wuhan and assessing the built environment of communities. Squalli (2017) explored the link between obesity and greenhouse gas emissions, emphasizing the role of transportation patterns in reducing environmental impact. Additionally, Glazier et al. (2014) highlighted the importance of walkable urban environments in addressing physical inactivity, overweight, and obesity, underscoring the role of urban planning in promoting public health.

With extensive research on obesity, scholars have been analyzing and assessing the relationship between obesity and various influencing factors from different perspectives. The relationship between transportation and obesity has emerged as a research hotspot. Scholars have considered that changing commuting patterns to increase daily energy expenditure can help alleviate obesity (Howell and Booth, 2022). Amir Samimi et al. (2009) developed a model to examine the impact of transportation and other variables on overall health and obesity among residents. Their findings indicate that developments centered around public transportation have a significant positive effect on both overall health and obesity reduction. Furthermore, reducing car usage by 1% can lead to a 0.4% reduction in obesity; Douglas M. King et al. concluded that there is an increasing amount of evidence suggesting that commuting through public transportation may be a potential measure to intervene in obesity (King and Jacobson, 2017); Martin Lindström explores the correlation between commuting modes and overweight/obesity, the study concludes that individuals who walk or bike to work have a significantly lower occurrence of overweight and obesity compared to the reference category of car driving (Lindström, 2008).

Additionally, researchers have also examined the relationship between transportation and diseases associated with obesity. For example, Kim et al. studied the effects of switching from private car commuting to public transportation on cardiovascular function and adiposity factors (Yae-Young et al., 2016). The findings suggest that a change in transportation mode contributes to improved cardiovascular function and obesity variables. Increasing physical activity through using public transportation can help prevent cardiovascular diseases and obesity. With further research and the introduction of the concept of active transportation, many scholars have conducted more in-depth studies on the relationship between the same mode of transportation and obesity in different scenarios. Green and Ferrari et al. explored the relationship between active transportation modes and obesity indicators (Ferrari et al., 2022; Green and Klein, 2011). Bassett et al. (2008) examined the association between active transportation and obesity rates across different countries, finding that nations with higher levels of active transportation generally have lower obesity rates. Similarly, Flint et al. (2014) evaluated whether active commuting is independently linked to objective biological markers of obesity and concluded that promoting active travel is an effective strategy for obesity prevention. Andersen (2016) and Laverty and Millett (2014) also emphasized that active transportation is a simple yet effective way to improve health and alleviate obesity-related issues. Additionally, Bell et al. (2002) suggested that reliance on motorized transportation may contribute to the global obesity epidemic, highlighting the promotion of active transportation as a potential preventive measure. Numerous scholars in their research have recognized that active transportation modes play a role in improving obesity-related issues.

These scholars have employed various models and experimental methods to delve into and confirm the factors influencing obesity, Mohamed utilized an OLS model to analyze the significant predictive factors of obesity related to transportation usage (Mohamed, 2018); Seliske et al. conducted a multilevel logistic regression to examine the correlation between urban sprawl, active transportation, moderate physical activity, and overweight/obesity (Seliske et al., 2012). Their findings indicated that urban sprawl is associated with active transportation but unrelated to obesity and overweight; She et al. assessed the impact of public transportation usage on obesity incidence at the county level in the United States, evaluating the potential of public transportation as an intervention for obesity (She et al., 2017). Regression analysis revealed that for every 1% increase in public transportation usage among the county population, the obesity incidence decreased by 0.221%.

This suggests that public transportation usage has the potential to contribute to reducing obesity rates among county populations. Based on the analysis of the literature, it is evident that there is still a lack of specific research on the correlation between obesity and transportation modes. The spatial correlation and clustering of obesity and transportation modes remain understudied areas, which are the focus of this study. Building upon existing research, this study aims to conduct a more in-depth investigation by utilizing

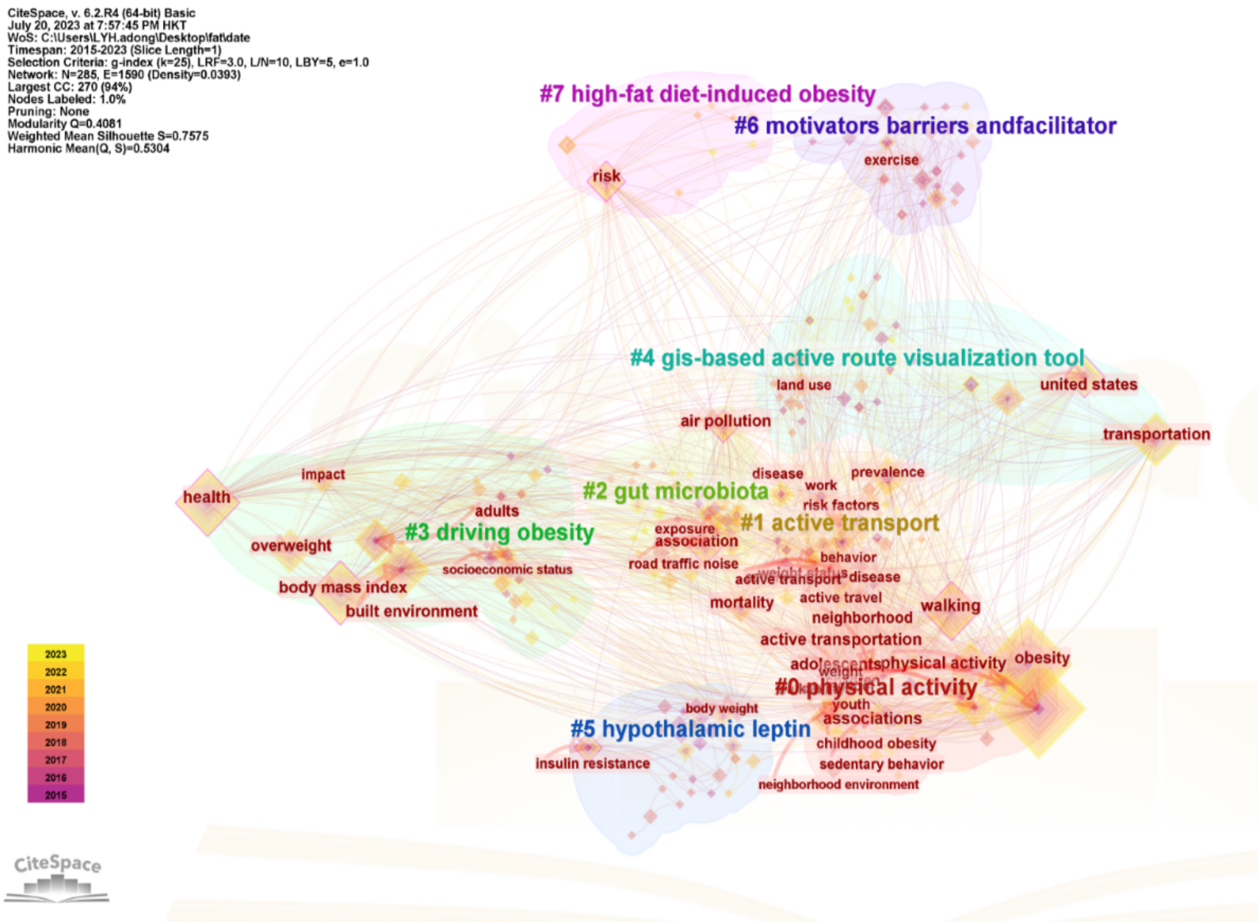

Figure 3 | Cluster analysis chart of 1281 literature on obesity and transportation

OLS and GWR models to statistically examine the impact characteristics of four transportation modes on obesity and overweight issues among urban residents. Additionally, it explores the spatial correlation and clustering of obesity and overweight levels among residents. By investigating the relationship between transportation modes and obesity from different perspectives, this study aims to provide new insights and recommendations for effectively alleviating the global obesity problem. Moreover, it seeks to fill the research gap in this area and provide a theoretical foundation for future studies in this direction.

Using CiteSpace, we analyzed 1,281 Web of Science articles on obesity and transportation, identifying key trends through keyword co-occurrence and clustering (Figure 3). Research has shifted from surface-level topics like "interventions" and "road traffic noise" to deeper issues such as "access," "food environment," and "cells" (Table 1), highlighting transportation's critical role in obesity. Scholars have explored factors like physical activity, driving behaviors, and motivational influences. Further studies on access and food environments could inform targeted policies. Advancing this field will enhance our understanding of the transportation-obesity link and support effective public health strategies.

As the world's second-largest economy, China has achieved remarkable growth, but this has also reshaped lifestyles, contributing to rising obesity and related chronic diseases. National data from 2015 showed that 43% of adults in China were overweight or obese (Wang et al., 2007). According to various surveys and research by the China, the average BMI of all age groups in China is increasing. The "Report on Nutrition and Chronic Diseases among Chinese Residents (2020)" provides comparisons of overweight and obesity rates among different age groups from 2015 to 2019 (Figure 4). It reveals that over half of Chinese adults are already overweight or obese, along with one-fifth of adolescents aged 6-17 and one-tenth of children under the age of 6. Calculated based on the absolute population, there are already 600 million people in China who are overweight or obese, ranking first globally. The fact that China has a population of 600 million people facing this health issue underscores the seriousness of overweight and obesity in the country.

Table 1 | Top 10 Keywords with the Strongest Citation Bursts

Keywords	Year	Strength	Begin	End	2015 - 2023
prevalence	2015	3	2015	2015	
interventions	2016	2.7	2016	2018	
road traffic noise	2017	1.94	2017	2018	
time	2018	2.15	2018	2018	
cancer	2020	2.59	2020	2021	
transportation	2015	2.41	2021	2021	
sedentary behavior	2019	1.94	2021	2023	
access	2015	3.13	2022	2023	
food environment	2022	2.25	2022	2023	
cells	2022	2.02	2022	2023	

Over the past 30 years, the prevalence of overweightedness and obesity has increased by an average of around 2.5 times across all age groups, indicating that this health issue persists and continues to expand. The urgency to conduct research and find relevant measures to address this problem is evident. In October 2016, China introduced the "Healthy China 2030 Plan," which aims to integrate health throughout the entire process of urban and rural planning, construction, and governance. Our team focuses on studying the relationship between residents' transportation patterns and overweight and obesity, aiming to identify the impact of different transportation modes on the issue.

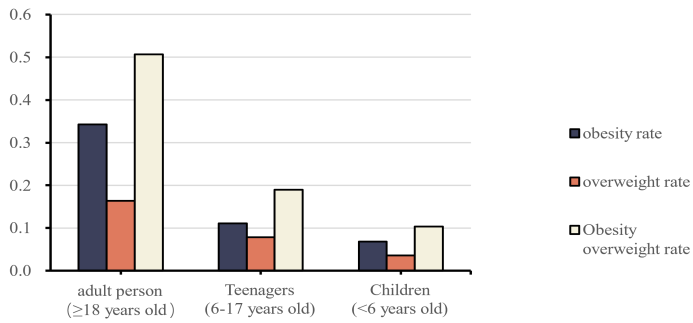

Figure 4 | Comparison of Overweight, Obesity Rates of Chinese Residents by Age Group, 2015-2019

(Source: Report on Nutrition and Chronic Disease Status of Chinese Residents,2020)

3. Data Sources and Research Methodology

3.1. Data Sources

In this study, Wuhan City is selected as the research object, with seven central urban districts including Jianghan District, Wuchang District, Qiaokou District, Qingshan District, Jiang'an District, Hongshan District, and Hanyang District (Figure 5) chosen as the study areas. A questionnaire survey was conducted to collect data on the health status, travel patterns, and economic conditions of residents in each district. The overall area covered by the study is approximately 860 km², with a population of 6.4 million. Such a survey scope and population size are considered sufficient to provide an adequate sample for subsequent research and to draw more convincing conclusions. In total, our team collected 10,328 questionnaires through a combination of online and offline methods.

3.2. Preliminary Data Analysis

The Body Mass Index (BMI) is a health indicator proposed by the World Health Organization (WHO) and recognized as a risk indicator for diseases. It is defined as an individual's weight in kilograms divided by the square of their height in meters. To assess the health status of the respondents, their BMI was calculated based on their height and weight, and the classification of adult body weight in "Standards for the Health Industry in the People's Republic of China" (Table 2) was referenced. The study found that 36% of the respondents had an abnormal health status, with 26% of them being overweight or obese. Fur-

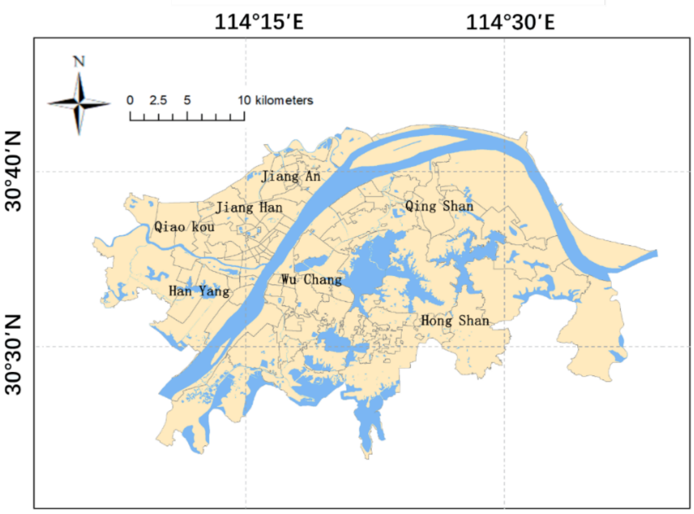

Figure 5 I The scope of the survey on the urban center of Wuhan

thermore, it was observed that among this large proportion of unhealthy individuals, 73% of the respondents were not familiar with the meaning of BMI, and 61% had little or no understanding of the risks associated with obesity and overweight issues (Figure 6). Therefore, based on these findings, this study aims to conduct in-depth research on urban residents with a BMI equal to or greater than 18.5, using BMI as an indicator of obesity and overweight levels among the population.

Based on the questionnaire responses regarding modes of transportation, our team categorized the respondents' transportation modes into four categories: walking, cycling, public transportation, and car usage. Based on this classification (as shown in Figure 7), it was found that walking had the highest number of participants, with a significantly high proportion of healthy individuals at 72%. Cycling followed closely behind at 68%, public transportation at 64%, and car usage at 59%. These findings suggest that the impact of transportation modes on obesity and overweight issues among residents is ranked as walking > cycling > public transportation > car usage. It is worth noting that the majority of residents' travel distances are concentrated within 0-2 kilometers. Therefore, when analyzing the relationship between transportation modes and obesity/overweight issues among residents, we will control the spatial unit at the street level to obtain more accurate conclusions.

3.3. Selection and Treatment of Transportation Travel Modes

The study variables consisted of four modes of transportation, namely walking, cycling, public transportation, and car usage, among residents in the central urban area of Wuhan. The coordinates of the respondents' origin and destination were derived from the geographic information provided in the question-

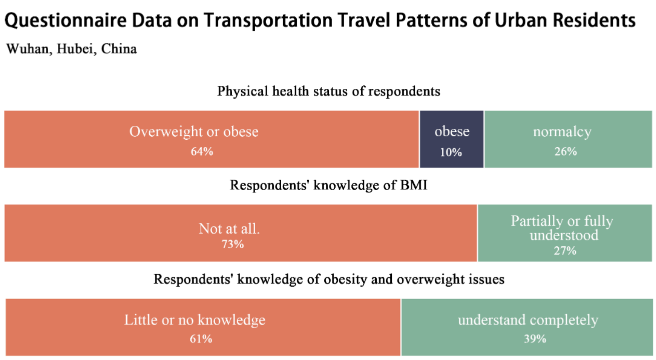

Figure 6 I Preliminary analysis of research data

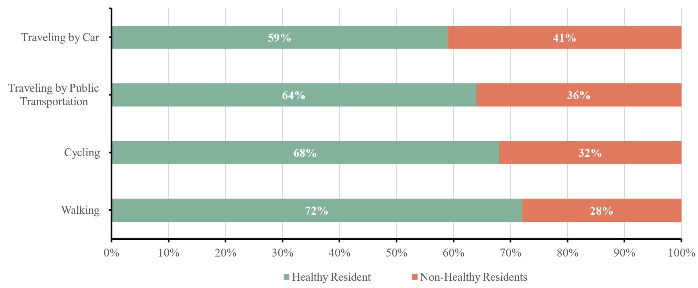

Figure 7 I Percentage of healthy residents choosing all modes of travel

Table 2 I Classification of adult body weight according to the "Health Industry Standard of the People's Republic of China"

Categorization	BMI（kg/m^2）
obese	BMI≥28
overweight	24≤BMI＜28
Normal weight.	18.5≤BMI＜24
underweight	BMI＜18.5

naire. The Baidu API was utilized to obtain OD (Origin-Destination) path data for all survey samples, which enabled the calculation of the actual distances for each transportation mode. In these distance calculations, the distances for walking and cycling were determined based on the shortest non-motorized road routes. The distance for public transportation comprised the fixed distance of the public transportation route plus the connecting distance between the origin/destination and the public transportation station. As for car usage, the distance was calculated based on the shortest motorized road route (Figure 8).

3.4. Research Methodology

$$y_i = \beta_0\left(U_i, V_i\right)x_{ik}\left(U_i, V_i\right) + \varepsilon_i\# \quad (2)$$

In this study, both the OLS (Ordinary Least Squares) model and GWR (Geographically Weighted Regression) model were employed to statistically test the impact characteristics of walking, cycling, public transportation, and car travel on obesity and overweight issues among urban residents, as described earlier. The OLS model was primarily used to analyze the relationship between a single dependent variable and multiple independent variables. It provides estimates of parameters on an average or global sense, allowing for factor selection based on the estimation results. On the other hand, the GWR model, an extension of the OLS model proposed by Brunsdon et al.(Brunsdon et al., 1999), incorporates the spatial locations of independent variable occurrence points into regression parameters. This allows the relationships between variables to vary with spatial location, accounting for spatial correlation and heterogeneity

$$W_{ij} = exp\left(-\frac{d_{ij}^2}{h^2}\right)\# \quad (3)$$

by assigning weights based on the decay function between each sample spatial location. Considering that the independent variables, such as walking, cycling, public transportation, and car travel, as well as the dependent variable, BMI (Body Mass Index) of residents, are presented in coordinate data form and exhibit spatial attributes, applying the GWR model enables better linear regression analysis of variable spatial heterogeneity. However, due to the sensitivity of the GWR model to multicollinearity among variables, it is advisable to include a limited number of

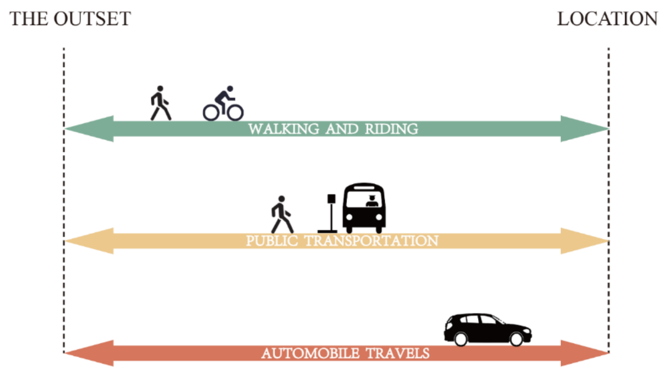

Figure 8 I Three modes of travel division

variables to ensure the accuracy of the GWR analysis. Therefore, it is common practice to conduct re-

$$y_i = \beta_0 + \sum_{k=1}^{n} \beta_k x_{ik} + \varepsilon_i\#(1)$$

gression analysis using the OLS model before performing GWR analysis to eliminate confounding factors.

The expressions of the OLS model (Equation 1) and the GWR model (Equation 2) are as follows:

The y_i is the dependent variable of the ith sample, β_0 is the intercept of the linear regression equation, β_k is the regression coefficient of the kth independent variable, x_{ik} is the value of the kth independent variable on i, and ε_i is the algorithm residual.

Therein $\beta_0(U_i,\ V_i)$ is the GWR intercept at $(U_i,\ V_i)$ spatial location, $\beta_k(U_i,\ V_i)$ is the weighted regression coefficient of the kth independent variable at$(U_i,\ V_i)$ spatial location, $x_{ik}(U_i,\ V_i)$ is the value of the kth independent variable at $(U_i,\ V_i)$,and ε_i is the algorithm residuals.

The key to the GWR model lies in the setting of the spatial weight matrix. In this study, ArcGIS 10.7 was used to select the Gaussian function as the kernel function of GWR analysis, with the kernel type being fixed. The expression of the kernel function is as follows:

In this case, $d_{ij}$is the spatial distance between sample i and sample j, and h is the optimal bandwidth. The GWR model is sensitive to the choice of bandwidth, and either too large or too small bandwidth may have an impact on the model fitting accuracy. Thus, based on the ArcGIS analysis platform, the Akaile Information Criterion (AIC) method is cho-

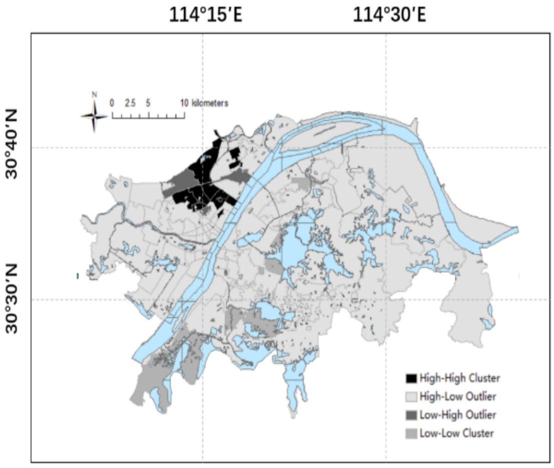

Figure 9 I Wuhan Localized Moran Index

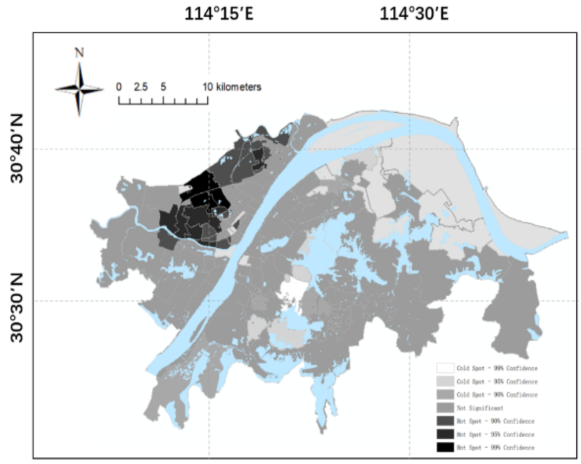

Figure 10 Analysis of localized hotspots in Wuhan

sen to determine the optimal bandwidth, and the optimal bandwidth can be determined when the AICc value of the model is the smallest.

4. Analysis of Results

4.1. Spatial Correlation Validation

Through the global statistical analysis of spatial correlation and the corresponding local statistical analysis, this paper examines the spatial correlation and degree of agglomeration of the degree of obesity and overweight among Wuhan residents.

The global statistical analysis of spatial correlation includes spatial autocorrelation analysis and high/low clustering analysis, the results of which (Table 3) rejected the hypothesis that the BMI values of the residents of Wuhan streets are not spatially correlated. In the spatial autocorrelation analysis, the global Moran's index was 0.261, indicating that there was a positive spatial correlation between the BMIs of Wuhan streets, while the z-value of 2.931 for the high/low clustering analysis indicated that this spatial correlation was more pronounced in the areas with higher BMIs.

In the local statistical analysis, firstly, three types of residents' obesity and overweight degree of high - high clustering, low - high anomaly and low - low clustering existed in Wuhan's central city streets through the local Moran's index analysis (Figure 9). High-high concentration is primarily found in the core areas of Hankou, Wuchang, and Hanyang along the river, Wuhan's traditional center, characterized by a dense population and well-developed transportation. Low-low concentration appears in the northeastern part of Wuhan, where heavy industries such as iron and steel and chemical enterprises dominate. This region has a self-contained social structure, leading to lower inter-regional travel demand, and its distance from Wuhan's center further limits outbound travel. Low-high anomalies are mainly observed in the streets of central Wuhan.

The low-high anomaly mainly occurs in the area within the second ring road of Wuhan, and is interspersed with the high-high agglomeration, which is also a more populated and conveniently located area in Wuhan. In addition, hotspot analysis was further utilized to identify the spatial clustering of areas with high and low values of statistical significance, respectively, thus validating the previously described characteristics of the distribution of the degree of overweight and obesity of the residents of each street (Figure 10). The above validation results only show that the spatial correlation of the degree of obesity and overweight is more significant in Wuhan city center, but the specific influence of different modes of transport on the residents' BMI is not yet clear, which is further analyzed by introducing the OLS model and the GWR model in this paper.

4.2. OLS Model Analysis

After standardizing the data of the variables, the results of the OLS model analysis are shown in Table 4, which shows that the VIF values of the variables as urban transport travel modes are lower than 7.5, so there is no redundancy in the variables. Among the variables, walking trip distance A_k, cycling trip distance B_k and car trip distance S_k passed the significance test with a robust p-value ≤ 0.05. Among them, the regression coefficients of walking travel distance, cycling travel distance and public transport travel distance are negative, especially the regression coefficient of walking travel distance reaches 0.3718, which is the highest value among the effective variables, and it also indicates that among the various types of transport modes described in this paper, walking travel distance has the greatest influence on the degree of obesity and overweight of Wuhan residents.

In order to compare the analytical validity of the OLS model and the GWR model, this paper will compare the adjusted R^2 and the Akaike information criterion of these two models. The R^2 value in the OLS diagnostic is 0.368, while the adjusted R^2 value is 0.267, which indicates that the OLS model is able to fit and explain about 26.7% of the total variance of the dependent variable, and furthermore the optimal bandwidth of the OLS model is determined in ArcGIS10.7 based on Gaussian function as well as the cross-validation method with a post-AICc value of 1087.26 The above diagnostics can be used to compare the analytical validity of the OLS model with the GWR model in the following section. for analytical validity comparison.

4.3. GWR Model Analysis

In the identification of travel modes influencing residents' obesity and overweight issues in various streets of Wuhan, the Geographically Weighted Regression (GWR) model demonstrates higher stability with an R^2 value of 0.675, which is an 83.42% improvement compared to the R^2 value of the Ordinary Least Squares (OLS) model. Additionally, the GWR model in this study has an AICc value of 1083.13, indicating a decrease of 4.13 compared to the AICc value of the OLS model. Normally, a decrease of 3.00 in AICc value suggests a significant improvement in the effectiveness of the model analysis. Hence, it can be observed that the GWR model yields higher effectiveness in analysis compared to the OLS model. Consequently, the subsequent analysis will be based on the GWR model to examine the impact characteristics of various transportation drivers on residents' obesity and overweight issues.

In the GWR model, standardized residuals following a random distribution indicate the effectiveness of the model. Based on the distribution of standardized residuals (Figure 11), it can be observed that none of the streets in Wuhan have standardized residuals exceeding 2.5 times the standardized residual, indicating that the residual test has been passed. Additionally, the model extension test based on the Moran's I index (Table 5) shows that the standardized residual

Table 3 | Global statistical results of spatial correlation of BMI distribution of Wuhan residents

Test items	exponents	Z-value	P-value	variance
High/Low Cluster Analysis	0.00011	3.52121	0.00021	<0.00001
Spatial autocorrelation analysis	0.26105	5.12252	0.00005	0.000576

Table 4 | Results of OLS model analysis of BMI distribution of Wuhan residents

Transportation travel patterns	regression coefficient	standard error	VIF	Robust t-value	Stable p-value
walking distance	-0.3718	0.1263	5.162	-2.944	0.042
cycling distance	-0.3165	0.24097	3.745	-1.313	0.031
public transportation distance	-0.1568	0.25982	2.965	-0.603	0.045
car travel distance	0.3566	0.38091	3.233	0.936	0.012

* $p<0.05$

confidence of this GWR model is greater than 99%. This suggests the absence of spatial clustering or dispersion, aligning with the characteristics of a random distribution.

The regression coefficients for walking distance A_k, cycling distance B_k, public transportation distance D_k, and car travel distance S_k are shown in Table 6. It can be observed that in geographically weighted regression analysis, the walking and cycling distances in different streets of Wuhan still exhibit a negative correlation with BMI values, while the car travel distance continues to show a positive correlation. This indicates that walking and cycling as modes of transportation clearly hinder the increase in BMI values, especially the walking distance, which has a high regression coefficient of 0.325 in the GWR model, suggesting a strong correlation with obesity and overweight issues among residents. In the GWR model, car travel distance shows a positive correlation with the prevalence of obesity and overweight among residents, indicating that the adoption of non-public transportation methods significantly reduces the physical exertion associated with travel, thereby making residents more susceptible to obesity and overweight issues. It should be noted that the above inferences are based on the provided information and regression coefficients. Further research and validation are required to accurately assess the relationship between walking, cycling, public transportation, car travel distances, and the prevalence of obesity and overweight among residents.

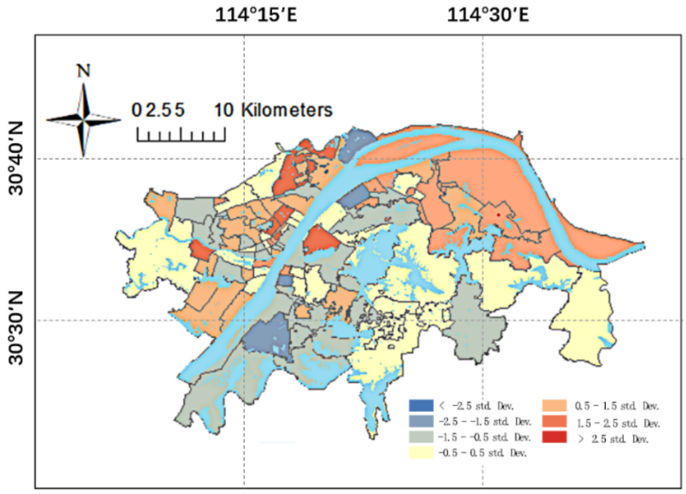

Figure 11 | Standardized Residual Distribution Plot

The GWR regression coefficient distributions of walking, cycling, and public transportation distances in each street of Wuhan are shown in Figures 12, 13, and 14. The regressions coefficients for all 93 streets in the study area were found to be negative, indicating a negative correlation between the distances of walking, cycling, and public transportation trips and the prevalence of obesity and overweight among residents. Furthermore, these coefficients were mainly concentrated in the southeast corner, with relatively lower values in the core urban areas and the lowest values in relatively remote areas. Contrasting with the distribution of public transportation in Wuhan (Figure

Table 5 | Standardized Residual Moran's Index Test for GWR Models

Test item	Numerical value
Moran Index	0.156
Z-score	4.375
P-value	<0.01

Table 6 | GWR modeling results

Transportation travel patterns	regression coefficient	Lower limit of regression coefficient	Upper limit of regression coefficient	standard error
walking distance	-0.325	-0.3258	-0.3247	0.106
cycling distance	-0.273	-0.2736	-0.2725	0.223
public transportation distance	-0.115	-0.1158	-0.1139	0.204
car travel distance	0.269	0.2681	0.2703	0.327

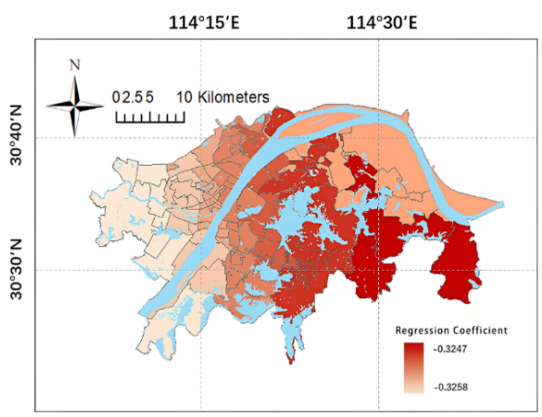

Figure 12 I Distribution of GWR Regression Coefficients (Walking Travel Distance) by Street in Wuhan

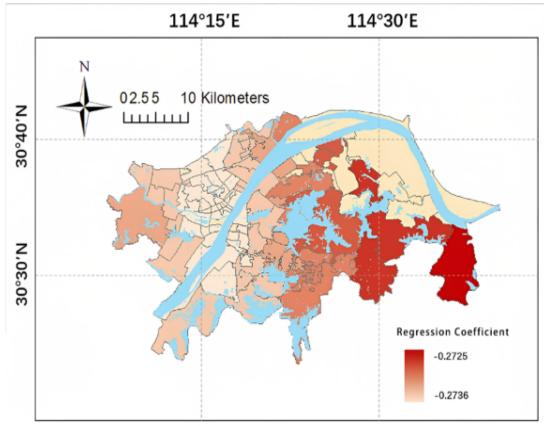

Figure 13 I Distribution of GWR regression coefficients (cycling trip distance) by streets in Wuhan

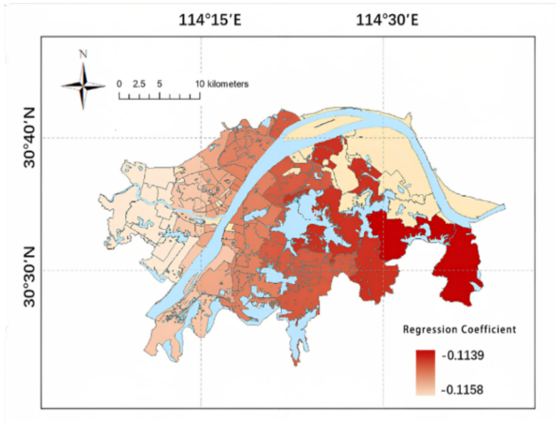

Figure 14 I Distribution of GWR regression coefficients (distance traveled by public transportation) by street in Wuhan

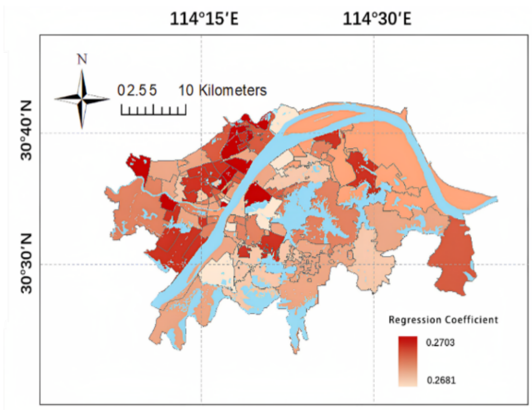

Figure 15 I Distribution of GWR regression coefficients (distance traveled by car) by street in Wuhan

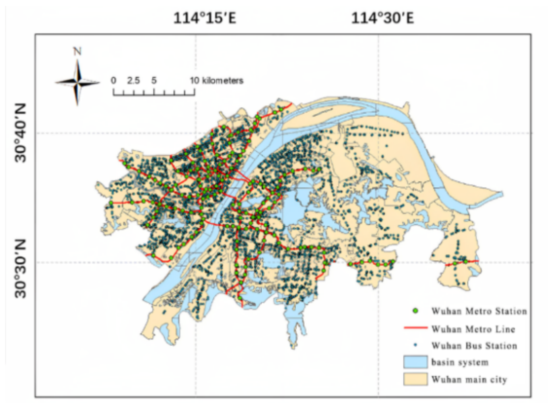

Figure 16 I Wuhan Public Transportation Map

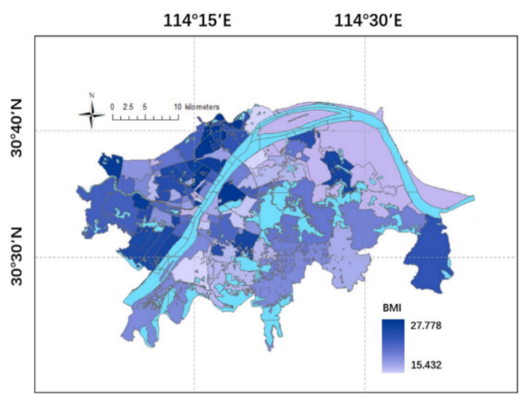

Figure 17 I Distribution of obesity and overweight in Wuhan

15), the areas near the main axis of the Yangtze River belong to densely populated residential areas with high public transportation coverage. In such cases, residents are more likely to choose walking or cycling as a mode of transport, thereby partially alleviating the issue of obesity and overweight.

In contrast, Figure 15 presents the GWR regression coefficient distribution of car travel distances among residents in each street of Wuhan. The regression coefficients for all 93 streets were found to be positive, indicating a positive correlation between car travel distances and the prevalence of obesity and overweight among residents. Compared to Figure 16, it can be observed that in areas with high public transportation coverage, there is a stronger relationship between car travel distances and obesity and overweight. This suggests that even when public transportation coverage is high, residents still tend to choose car travel over public transportation or other non-motorized modes of transport, thereby exacerbating the problem of obesity and overweight.

According to the distribution map of obesity and overweight among residents in Wuhan (Figure 17), it can be observed that areas such as Jiang'an District, the western part of Qiaokou District, the southern part of Hanyang District, and the southeastern part of Hongshan District have a more serious problem of obesity and overweight among residents. By comparing it with the distribution map of public transportation in Wuhan, it can be inferred that there is a positive correlation between the density of public transportation stations and the issue of obesity and overweight among residents. This may be because areas with high coverage of public transportation stations belong to the most developed areas of Wuhan. Due to the availability of comprehensive facilities and a self-sustaining social life system, residents in these areas have shorter daily travel distances. Therefore, urban residents are more likely to choose walking or cycling as a mode of transport. Compared to walking or cycling, using public transportation requires less physical effort.

5. Conclusions and Recommendations

5.1. Conclusions

From an overall perspective, 26% of the respondents in the sample were overweight or obese, and 73% of the respondents were not familiar with the meaning of BMI. Additionally, 61% of the respondents had little or no understanding of the health risks associated with obesity and overweight. From these findings, it can be inferred that residents have a low level of awareness and concern regarding obesity and overweight issues. The current situation of obesity and overweight among residents is not optimistic.

Based on the analysis of specific questionnaire items, we further explored the factors influencing obesity and overweight issues among urban residents in different modes of transportation. The following conclusions were drawn:

1) Among the four typical modes of transportation, namely walking, cycling, public transportation, and car use, there is a negative correlation between the distance of walking, cycling, and public transportation and the prevalence of obesity and overweight among residents. However, the negative correlation is least significant for public transportation distance, while there is a positive correlation between car use distance and the prevalence of obesity and overweight.
2) The density of public transportation stops is positively correlated with the degree of obesity and overweight among residents. Moreover, the density of public transportation stops also affects the correlation between transportation modes and obesity and overweight issues. In areas with high coverage of public transportation stops, both public transportation and car use distances have a stronger correlation with obesity and overweight. In areas with low coverage of public transportation stops, the correlation between walking, cycling distances, and obesity and overweight is more pronounced.
3) There are significant variations in the distribution of obesity levels among residents in different regions of Wuhan. For instance, obesity and overweight are more severe in areas such as Jiang'an District, the western part of Qiaokou District, the southern part of Hanyang District, and the southeastern part of Hongshan District.

5.2. Recommendations

Based on the analysis above, it can be inferred that residents' choices of walking, cycling, and public transportation can improve obesity issues. Encouraging and facilitating the use of these three modes of transportation is an effective measure to reduce obesity among residents. Firstly, optimizing the slow transportation system and constructing urban greenways are crucial. For example, Wuhan's slow transportation system has a serious issue of "acquired deformity", mainly characterized by the absence of dedicated bicycle lanes on many roads and the obstruction of pedestrian pathways or bicycle lanes by barriers or random parking. These problems directly discourage residents from choosing walking or cycling as their daily modes of transportation, thus affecting the obesity and overweight issues among residents.

Therefore, Wuhan needs to optimize its slow transportation system by constructing a more comprehensive independent network for motorized and non-motorized vehicles, establishing dedicated bicycle lanes, and strictly prohibiting motor vehicles from entering these lanes. Secondly, benefiting from its unique natural environment, Wuhan has built over 350 “pocket parks” and greenways extending over 2,000 kilometers as of October 2022. Wuhan needs to maintain the efficiency of greenway construction and continue improving the grid structure of greenways while connecting them with other service systems in line with the city's development pattern. The optimization of the slow transportation system and the construction of urban greenways provide residents with convenient and safe walking and cycling environments, thereby increasing their inclination to choose non-motorized modes of transportation. This will help alleviate the obesity and overweight issues among Wuhan residents. In addition, you can also optimize the public transport and shared transport planning layout, combined with the regional distribution of obese overweight residents of Wuhan in this paper and the distribution of public transport can be proposed for the city managers. For example, in areas such as Jiangan District and Qiaokou District in the west with broad public transport coverage and a significant problem of obesity and overweight among residents, a centralized placement of public transport stations and shared bicycles can be implemented to create a travel system that combines public transport and bike-sharing. This can help to alleviate the issue of obesity and overweight among residents. In the southeastern part of Hongshan District and other public transportation station coverage is small and the problem of obesity and overweight residents is serious in the region for decentralized placement, expanding the density of shared bicycle coverage, and prompting the residents to non-motorized travel, thereby improving the problem of obesity and overweight.

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Ecological Spatial Restoration in Gannan Prefecture Based on the Coupling of Ecological Security Pattern and Ecological Problems

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KEYWORDS

Ecological Network,
Ecological Security Pattern,
Ecological Problem Identification,
Ecological Space Restoration

ABSTRACT

Ecological fragmentation, resource depletion, and soil erosion significantly impact ecosystems, making ecological restoration crucial for maintaining and enhancing ecosystem services. This study explores strategies for ecological spatial restoration in Gannan Tibetan Autonomous Prefecture by integrating ecological security patterns and ecological problems. Using ecological remote sensing indices and morphological spatial pattern analysis, we identified ecological sources, resistance surfaces, and corridors to construct an ecological security pattern. Simultaneously, ecological problem areas were identified through an ecological problem index (EPI) based on the “mountain, water, forest, farmland, lake, grass, and sand” framework. By coupling the ecological security pattern with problem regions through spatial and regional coordination, a multi-level restoration strategy is proposed, emphasizing ecological source protection, corridor construction, and problem area restoration. These strategies aim to promote sustainable ecological development in Gannan Prefecture.

1. Introduction

Gannan Tibetan Autonomous Prefecture has a unique plateau ecosystem and rich biodiversity. In recent years, the region has faced a series of ecological problems such as grassland degradation, soil erosion, and biodiversity decline (Lv, et al., 2023), which not only threaten the livelihoods of local residents, but also pose challenges to the ecological security pattern of the entire region (Lin, et al., 2021). In the context of ecological civilization construction in the new era, China's concept of "mountain, water, forest, field, lake, grass and sand are a community of life" came into being (Gao, et al., 2022), and the close connection and mutual influence among various ecological elements can make the ecosystem an organic whole (Dong, et al., 2020). How to comprehensively build an ecological security pattern, how to scientifically apply the concept of mountain, water, forest, field, lake, grass and sand life community to ecological space restoration, and how to coordinate all natural elements to achieve "unified protection and unified restoration" have become hot issues that need to

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be solved urgently in ecological protection and restoration.

At present, the construction of ecological security pattern has aroused wide attention in the world, and scholars with different professional backgrounds have constructed ecological security pattern from different directions.The international research on ecological security pattern mainly includes five aspects and directions. The first is to adopt the framework of "ecological source - ecological resistance surface - ecological corridor", and strengthen the relevant technology and content within the framework.In the direction of ecological source recognition, some scholars adopt different scenario recognition methods of “structure-pattern-function" (Hou, et al., 2024) and “pattern-function-stability" (Qiao, et al., 2024); Other scholars have integrated multi-factor identification of ecological sources (Cao, et al., 2024; Wang, et al., 2024); Some scholars also considered the innovation of ecological source and resistance surface, combined with landscape index to optimize ecological resources, and considered the spatial differentiation of ecological resistance from the microscopic perspective of landslide sensitivity assessment (Li, et al., 2024).In addition to innovation and research within the framework, some scholars also add innovation points on the basis of the framework; Some scholars draw on the basic theory of "source-resistance-corridor" and comprehensively consider the ecosystem service zoning and supply and demand relationship (Liu, et al., 2024; Wu, et al., 2024); Some construct a "water-energy-food" framework, and identify and optimize the ecological security pattern from the perspective of ecosystem services related to the three (Ding, et al., 2024).The second is to write from different perspectives on the construction of ecological security pattern. For example, from the perspective of ecological resilience assessment of ecosystem resistance-ecosystem adaptive-ecosystem resilience framework (Jie, et al., 2024); Landscape ecological risk assessment from the perspective of potential-connection-resilience framework (Bai, et al., 2023); From a regional and interregional perspective (Liu, et al., 2024); With the technological innovation, some use the XGBoost (limit gradient lift) -MCR (minimum cumulative resistance) algorithm (Sun, et al., 2024) and introduce the ordered weighted average (OWA) model and the quantitative perspective of the ant colony algorithm model (Pan, et al., 2023).The third is to break the traditional ecological security pattern construction and introduce new aspects of ecological security pattern construction with the help of traditional paradigm.For example, Hui He and other scholars evaluated the suitable habitat for the ecological restoration of giant panda habitat and optimized the ecological security pattern (He, et al., 2024) ;Zeng et al. (2024) studied the ecological security pattern in the alpine wetland grassland region; Zilong Chen et al. have studied the dynamic changes in the pattern of wading ecological security in the area over the past 20 years (Chen, et al., 2023), Contribute to regional ecological planning and sustainable water management.The fourth is to construct the ecological security pattern from different time dimensions, study its changes at different times, summarize the current situation, and guide and predict the future planning and management.For example, most of the scholars are studying the regional status characteristics and spatio-temporal data characteristics from 2000 to 2020. The ecological security pattern of "grid-county-basin" at different scales (Chen, et al., 2023) or "point-line-surface" at different angles (Zhang, et al., 2024) was analyzed;The further prediction for the future is to analyze the change and driving mechanism of ecological carrying capacity in the study area from 1990 to 2040 (Zhang, et al., 2023), The idea of "history-present-future" to construct ecological security pattern is proposed, and the time scale of the study is longer, and the future is also predicted.Fifth, a lot of research has been done on the application of ecological security pattern after construction. For example, the most direct and widespread application is the demarcation of ecological control areas to determine the priority areas for ecological protection and restoration (Gao, et al., 2022; Wang, et al., 2024; Ran, et al., 2022);Some scholars build multi-strength ESP and put forward differentiated management strategies (Jiang, et al., 2024); The advantages and economic countermeasures of ecological carbon sink under the ecological security pattern are also explored (Wang, et al., 2024).

At present, many international scholars' ecological space restoration identification is based on the condition of ecological security pattern (Lan, et al., 2024; Yang, et al., 2024), However, there are also other perspectives to realize the identification of ecological space restoration areas and points.For example, based on the concept of ecological environment restoration, the optimization strategy of green settlement landscape is studied (Liu, et al., 2023); From the Angle of human-land relationship and structuralism (Chen, et al., 2022), The evaluation scheme of ecological space based on ecosystem services and the planning control of land planning based on ecological protection and restoration were constructed; Some have also built five ecological performance systems with earth boundary and ecological pressure as indicators (Zhao, et al., 2024), As a basis for prioritizing ecological restoration areas and implementing zoning control;Kun Yu et al. proposed an assessment framework for the comprehensive effect of ecological restoration that included public satisfaction (Yu, et al., 2024), The performance before and after ecological restoration was analyzed from 2015 to 2021;Yuyang Wang and other scholars put forward targeted ecological restoration suggestions from the perspectives of habitat, ecology and life from both theoretical and practical perspectives (Wang, et al., 2024). Some scholars also comprehensively assess the present ecological situation and put forward corresponding measures for ecological restoration regionalization based on the past ecosystem health level (Chen, et al., 2024).

Most of the above scholars use a single factor to identify the ecological restoration space, and the current research on the identification under the comprehensive multi-factor condition is relatively scarce,Bo Han and other scholars have broken the disadvantages of studying ecological problems on a single ecosystem or a single scale (Han, et al., 2021), A multi-scale evaluation framework for land and air ecological restoration planning strategy based on PSR perspective and landscape, ecology and GIS methods was proposed; Some scholars have considered the estimation of the recovery capacity of the muddy coast and the selection of two conceptual models of the common technical measures for the ecological restoration of the muddy coast (Wu, et al., 2023), Determine the ecological restoration path of the study area;A comprehensive approach coupling ecological benefits and restoration costs has been proposed (Dong, et al., 2024), giving priority to the restoration of abandoned mines.In terms of the selection of research areas, many scholars choose the southern region with better ecological environment than the northern region, and there are few studies on some special environmental regions, such as the ecological restoration region of dryland in China (Han, et al., 2023) and the northwestern region of Qinghai-Tibet Plateau (Tang, et al., 2024).

Therefore, the construction of ecological security pattern has formed the research paradigm of "ecological source - ecological resistance surface - ecological corridor" (Duan, et al., 2022), but the research on the refinement and improvement of the three links is also extensive. Firstly, the multi-factor synthesis method is still lacking in the identification of ecological sources, and the improvement in this aspect is still a hot spot. Secondly, the selection of ecological resistance surface factors is basically started from the three aspects of terrain, landscape and human factors, and there are more and more factors. Finally, the identification of ecological corridors has made a big leap since the introduction of linkage mapper. In addition, with the concept of the community of "mountains, rivers, forests, fields, lakes, grass and sand" proposed, some scholars also use it as a targeted indicator to identify ecological problems, and then identify the space for ecological restoration. However, this method is still too lacking, and a comprehensive multi-factor should be considered to identify the ecological restoration space. Therefore, the research of ecological spatial restoration is moving towards a more comprehensive and systematic direction, and the future trend will focus on the in-depth coupling and synergistic development of multiple factors, the quantitative identification of ecological restoration space and the proposal of optimization strategies, especially in the face of global challenges such as climate change, resource management and socio-economic changes.

Considering the special position of Gannan prefecture at the junction of three provinces and the current situation of unbalanced development of ecosystem, this study aims to explore how to realize the ecological spatial restoration strategy according to local conditions in Gannan Prefecture. Therefore, based on the dual factors of ecological security pattern and ecological problems, this study identified ecological spatial restoration strategies, and established a multi-directional restoration strategy of "point-line-plane". Firstly, ecological security pattern and ecological pattern zoning are constructed through the paradigm of "ecological source - ecological resistance surface - ecological corridor - ecological key point". Then, comprehensive indicators for ecological problem identification are established to identify ecological problem regions in Gannan Prefecture based on the concept of "mountains, rivers, forests, fields, lakes, grasses and sand" community. Finally, the key areas for ecological restoration and protection in the future are determined by coupling ecological pattern and ecological problem zones, and corresponding strategies and measures are formulated to achieve sus-

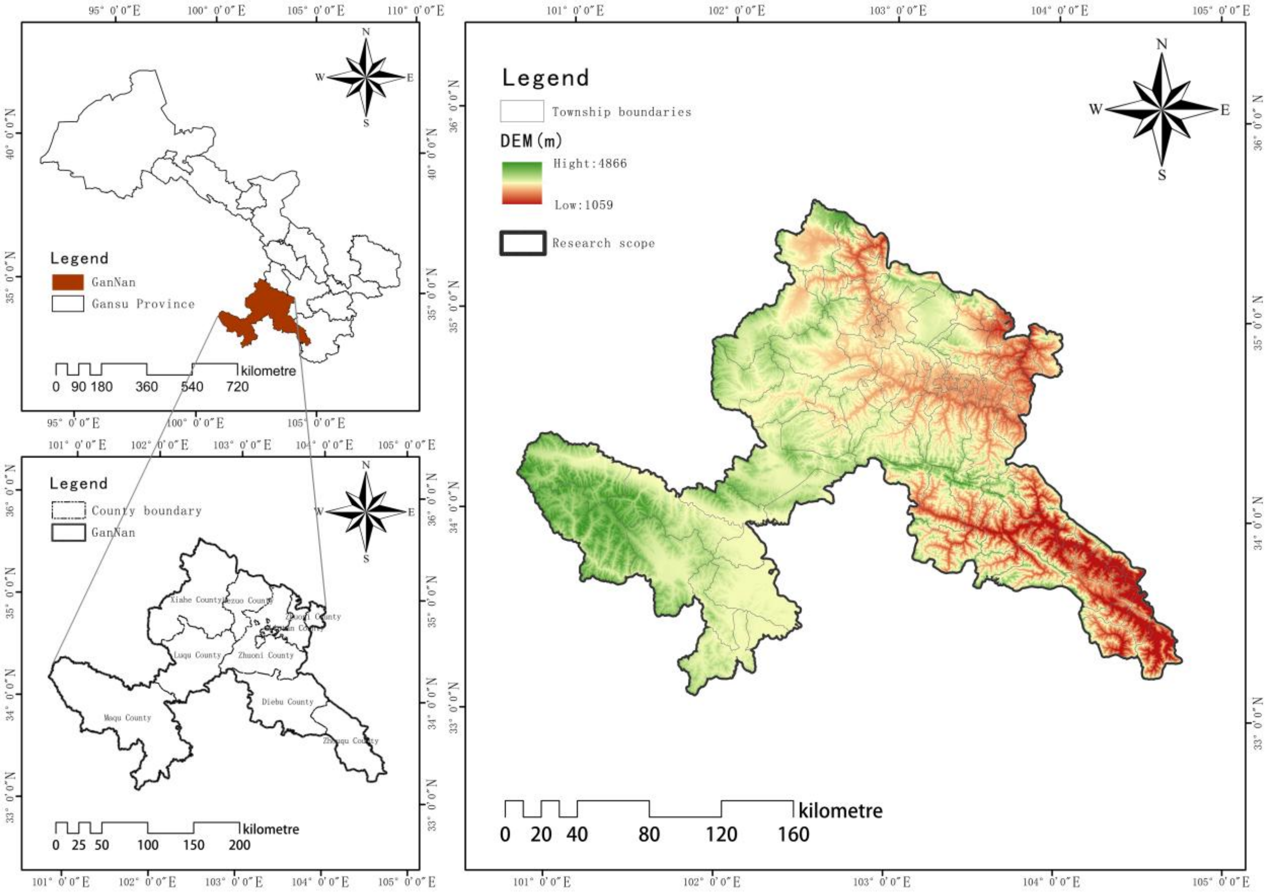

Figure 1 | Location map of Gannan Prefecture

tainable ecological development and the construction of ecological civilization. Based on this, this paper aims to solve the following problems: 1) How to establish a more accurate and comprehensive ecological source and ecological source point? 2) How to identify ecological problems according to local conditions? 3) How to systematically and quantitatively identify ecological restoration space? 4) How to formulate ecological restoration strategies based on the special geographical environment of Gannan Prefecture? As a beneficial supplement, this study will provide scientific and accurate ecological restoration programs for Gannan Prefecture and similar northwest regions, promote the construction of ecological civilization, and provide references for ecological planning and territorial spatial planning to achieve regional ecological sustainable development.

2. Materials and Data

2.1. Overview of the Study Area

Gannan Tibetan Autonomous Prefecture is located in the southwest of Gansu Province (Zou, et al., 2022). It has jurisdiction over seven counties and one city, namely Lintan, Zhuoni, Dibe, Zhouqu, Xiahe, Maqu and Luqu, and Hezuo City (Figure. 1). It is 360.7 kilometers long from east to west and 270.9 kilometers wide from north to south, with a total area of 45,000 square kilometers. The average elevation of the state is between 3,000 and 4,000 meters, with the lowest point at Guazigou Estuary in Zhouqu County at 1,172 meters above sea level and the highest at 4,920 meters. The south is Diemin mountains, the east is hilly mountains, the west is flat grassland, the terrain is high in the northwest, low in the southeast, and tilted from northwest to southeast. Gannan Prefecture has unique features such as special geographical location, multi-cultural gathering and frequent natural disasters, so it is typical and exemplary to study its ecological space restoration.

2.2. Data Sources

All the data in this paper come from official websites, including geospatial data Cloud website, Resources and Environmental Science Data Center, Statistics Bureau of Gannan Tibetan Autonomous Prefecture, National Earth System Science Data Cen-

Table 1 | Data sources

Data Types	Data Source	Content	Specification
Landsat8 OLI remote sensing image data	Geospatial data cloud （https://www.gscloud.cn/search）	Remote sensing image data of Gannan Prefecture	July - August, 2021-2022; Spatial resolution is 30M; Image cloud cover is less than 5%
DEM data		ASTER GDEM 30M resolution digital elevation data	2022; Spatial resolution is 30M
LUCC data	Resource and Environmental Science Data Center（https://www.resdc.cn/Default.aspx）	Raster data of land use remote sensing monitoring	2022; Spatial resolution is 30M
GDP data		GDP spatial distribution kilometer grid dataset	2022; The spatial resolution is 1KM
Township data of Gannan Prefecture	Statistics Bureau of Gannan Tibetan Autonomous Prefecture（http://tjj.gnzrmzf.gov.cn/index.htm）	Population data; Crop data; Livestock inventory data, etc	2022
POI data	Amap platform（https://www.amap.com/）	Scenic spots, commercial service facilities, transportation facilities, tourist attractions POI data	2022
Road data	Open Street Map(https://www.openstreetmap.org)	Gannan road vector data	2022
Drainage data		Gannan water system vector data	2022

ter platform, Amap Platform and Open Street Map data platform, etc. (Table 1).

2.3. Research Framework

This paper identifies areas for ecological protection and restoration based on the superposition of ecological security pattern and ecological problem identification. On this basis, a multi-directional strategy of "point-line-surface" is proposed, and reasonable planning and management is proposed at last (Figure 2).

3. Methods

3.1. Ecological Source Identification

3.1.1. Ecological Remote Sensing Index

Ecological Remote Sensing Index (RSEI) is a method to evaluate ecological environment quality by remote sensing technology. It is usually based on satellite remote sensing images and reflects various attributes of ecological environment by analyzing spectral characteristics of the surface. In this study, four ecological remote sensing indexes, namely vegetation index (NDVI), humidity index (WET), surface temperature (LST) and building index (NDBSI), are selected as ecological remote sensing indexes, which can comprehensively reflect the ecological status of a region. The formula is as follows:

$$NDVI = \frac{b_5 - b_4}{b_5 + b_4} \quad (1)$$

$$WET = 0.151 \times b_2 + 0.1973 \times b_3 + 0.3283 \times b_4 + 0.3407 \times b_5 - 0.7117 \times b_6 - 0.4559 \times b_7 \quad (2)$$

$$LST = \frac{1321.08}{a\,log(\frac{774.89}{b_1} + 1)} - 273 \quad (3)$$

$$SI = \frac{(b_4 + b_6) - (b_2 + b_5)}{(b_6 + b_4) + (b_2 + b_5)} \quad (4)$$

$$IBI = \frac{\frac{2 \times b_5}{b_5 + b_4} - \frac{b_4}{b_4 + b_3} + \frac{b_2}{b_2 + b_5}}{\frac{2 \times b_5}{b_5 + b_4} + \frac{b_4}{b_4 + b_3} + \frac{b_2}{b_2 + b_5}} \quad (5)$$

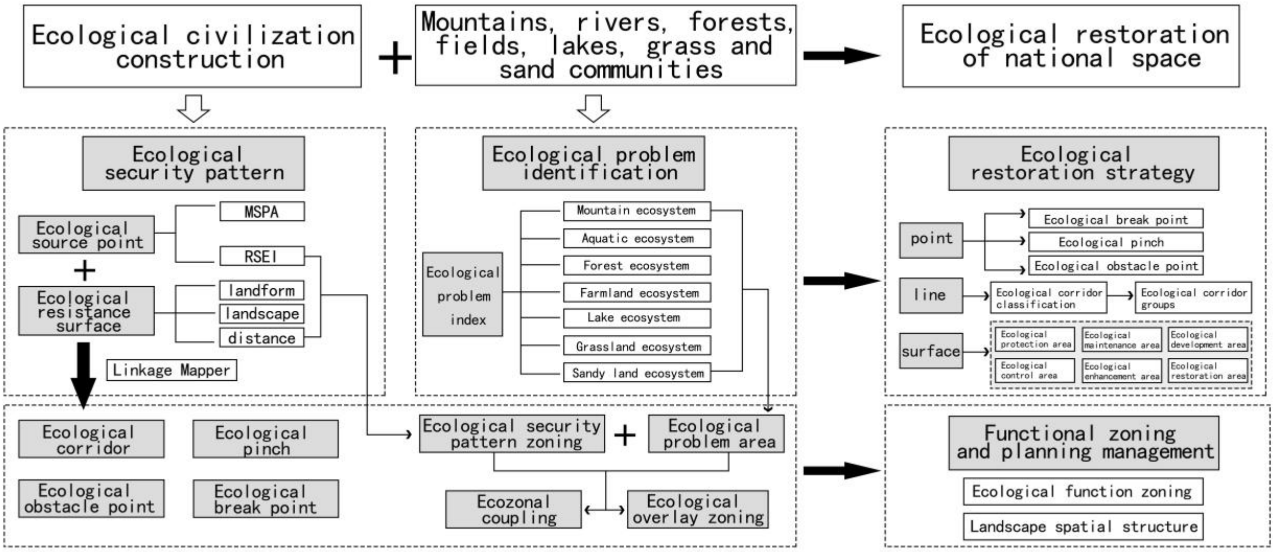

Figure 2 | Research framework

$$NDBSI = \frac{IBI + SI}{2} \quad (6)$$

Where, b1, b2, b3, b4, b5, b6 and b7 are respectively coastal band, blue band, green band, red band, near infrared band, shortwave infrared 1 and shortwave infrared 2.

The ecological remote sensing index was synthesized by principal component analysis (PCA). Before synthesizing the ecological remote sensing index, it is necessary to conduct standardized dimensional-1 processing on related indicators, and the standardization formula of each indicator is as follows:

Where, NI is the index after standardization; Imin and Imax are the minimum and maximum values.

Principal component analysis was carried out on the normalized new indicators, and principal component (PCA) containing the main features of the four indicators was selected, and then PCA was subtracted from 1 as the initial ecological index RSEI. The formula was as follows:

$$NI = \frac{I + I_{min}}{I_{max} - I_{min}} \quad (7)$$

3.1.2. Morphological Spatial Pattern Analysis

Morphological Spatial Pattern Analysis (MSPA) is an image processing method based on the principle of mathematical morphology, which is used to analyze and recognize landscape spatial patterns. MSPA is combined with ArcGIS10.6 to pre-process land use data, convert it into binary data (foreground and background), and then use the specific analysis tool Guidos software for MSPA analysis. MSPA can identify important habitat patches and corridors in the study area from the pixel level, such as core area, bridge area, ring area, branch area, edge area, pore and island patch.

$$RSEL = 1 - PCA(NDVI, WET, LST, NDBSI) \quad (8)$$

3.2. Ecological Resistance Surface

Landscape Resistance refers to the degree of obstacles encountered by individual organisms or material flows in a landscape. It is used to describe the resistance of living things to migration, diffusion or energy flow in a landscape. In this study, seven resistance factors including DEM, slope, slope direction, LUCC, NDVI, distance from road and distance from water system were selected based on previous research results and regional characteristics of Gannan Prefecture, and a comprehensive resistance surface was constructed by grid weighted superposition of ArcGIS10.6 software. The specific resistance values and weights of each factor were shown in Table 2.

3.3. Ecological Network Construction

Linkage Mapper in ArcGIS 10.6 software was used in this study to construct ecological corridor, ecological sandwich point and ecological barrier point in Gannan Prefecture.

Linkage Mapper is an open source toolset designed for ArcGIS that uses integrated circuit theory to model potential movement paths of species across complex landscapes and prioritizes these movement paths based on ecological cost and connectivity assessments.

Linkage Pathways Tool in Linkage Mapper is a circuit theory-based tool that identifies ecological corridors by simulating the flow of electricity through a network. This approach takes into account landscape connectivity, species dispersal potential, and ecological processes to determine the best path for species to move through the landscape.

Eco pinch points run in the Pinchpoint Mapper tool. It requires the invocation of the Circuitscape program, which is used to identify key ecological pinpoints within the established ecological corridor network. By analyzing the minimum cost path and combining with circuit theory, the important alternative path and pinch area are identified.

The ecological Barrier point is realized by using Barrier Mapper tool. The circuit theory is applied to calculate and quantify the potential of connectivity improvement through analysis on the resistance surface data, and the important barrier affecting the quality of the channel can be detected, namely, the ecological barrier point.

3.4. Ecological Problem Identification

The identification of territorial ecological problems is based on the life community concept of "mountains, rivers, forests, fields, lakes, grass and sand". The Ecological Problems Index (EPI) of Gannan Prefecture was constructed from seven factors, namely mountain ecosystem, water ecosystem, forest ecosystem, farmland ecosystem, lake ecosystem, grassland ecosystem and sandy ecosystem, weighted by superposition of prominent ecological problems in Gannan Prefecture. The calculation formula is as follows:

$$EPI = \sum_{i=1}^{u} K_i \times W_j \tag{9}$$

Where ,EPI is the ecological problem index; Ki is the standardized ecological problem index value; u is the number of ecological problem indicators; Wj is the weight of each ecological problem index. When the EPI value is larger, it means that the ecological problems in the key area to be repaired are more prominent, and vice versa.

3.5. Coupling Coordination Degree

The coupling coordination degree model is a method used to analyze and evaluate the level of coordination development between two or more systems. It is mainly used to assess the degree of interaction, interdependence and interdependence between different systems, and the impact of these in-

Table 2 | Resistance factor assignment index

Resistance factors		Weight	Assign				
			1	2	3	4	5
landform	DEM/（m）	0.1307	＜2400	2400-2800	2800-3200	3200-3600	＞3600
	slope/（°）	0.0997	＜10	10-20	20-30	30-40	＞40
	aspect/（m）	0.1142	-1	0-45	45-135	135-315	＞315
landscape	LUCC	0.2546	Artificial surface	Forest/shrub	Water body/ bare land	Cultivated land/ Wetland	meadow
	NDVI	0.1497	0.8-1	0.6-0.8	0.3-0.6	0.1-0.3	0-0.1
distance	Distance from road/（m）	0.1419	＞2000	1500-2000	1000-1500	500-1000	＜500
	Distance from water/（m）	0.1092	＞2000	1500-2000	1000-1500	500-1000	＜500

teractions on the overall coordinated development. The core concepts of the coupling coordination degree model include coupling degree (C value) and coordination degree (D value), and the formula is:

$$C = \frac{1}{n}\left(\prod_{i=1}^{n}\frac{U_i}{U_i+\lambda}\right) \tag{10}$$

$$T = \sum_{i=1}^{n}\beta_i U_i \tag{11}$$

$$D = \sqrt{C \times T} \tag{12}$$

Where, U_i represents a certain index value of each subsystem, n is the number of subsystems; λ is an adjustment factor greater than 0, which is used to adjust the sensitivity of the coupling degree. Is the weight of the I-th subsystem; Is the standardized subsystem index value; D is coupling coordination degree; C is for coupling degree; T is the coordination index.

The classification of coupling coordination degree depends on the interval of coordination degree D value, as shown in Table 3.

4. Results

4.1. Ecological Source Point Selection

4.1.1. Ecological Remote Sensing Index

The Landsat 8 LI TIRS data of Gannan Prefecture were preprocessed, corrected, merged and clipped on ENVI software to obtain a pre-data. The four indices of ecological remote sensing, namely NDVI, WET, LST and NDBSI, were calculated through the above formula, as shown in Figure 3 below. Gannan Prefecture has high vegetation coverage and humidity, but low overall humidity and uneven distribution of surface temperature.

4.1.2. MSPA and RSEI

In this study, by using the 2022 LUCC data of Gannan Prefecture, important patches in the study area were identified, such as core area, bridge area, ring road area, feeder area, edge area, pore and island patch, etc., as shown in Figure 4 (a). In this study, the ecological remote sensing index was generated according to the weight of $NDVI \times 0.6923 + WET \times 0.2655 + LST \times 0.0374 + NDBSI \times 0.0048$, as shown in Figure 4 (b).

As can be seen from Figure 4, the overall ecological situation of Gannan Prefecture is relatively good, except that the ecology of northeast and southeast

Table 3 | Classification standard of coupling coordination degree

Coupling coordination degree D value size interval	Coupling coordination level	Degree of coupling coordination
[0,0.1)	1	Extremely dysfunctional recession class
[0.1,0.2)	2	Severe dysfunctions recession class
[0.2,0.3)	3	Moderate dysfunction decline category
[0.3,0.4)	4	Mild disorder decline class
[0.4,0.5)	5	On the verge of dysfunctions
[0.5,0.6)	6	Barely coordinated development class
[0.6,0.7)	7	Primary coordinated development category
[0.7,0.8)	8	Intermediate coordinated development category
[0.8,0.9)	9	Well coordinated development class
[0.9,1]	10	Quality coordinated development category

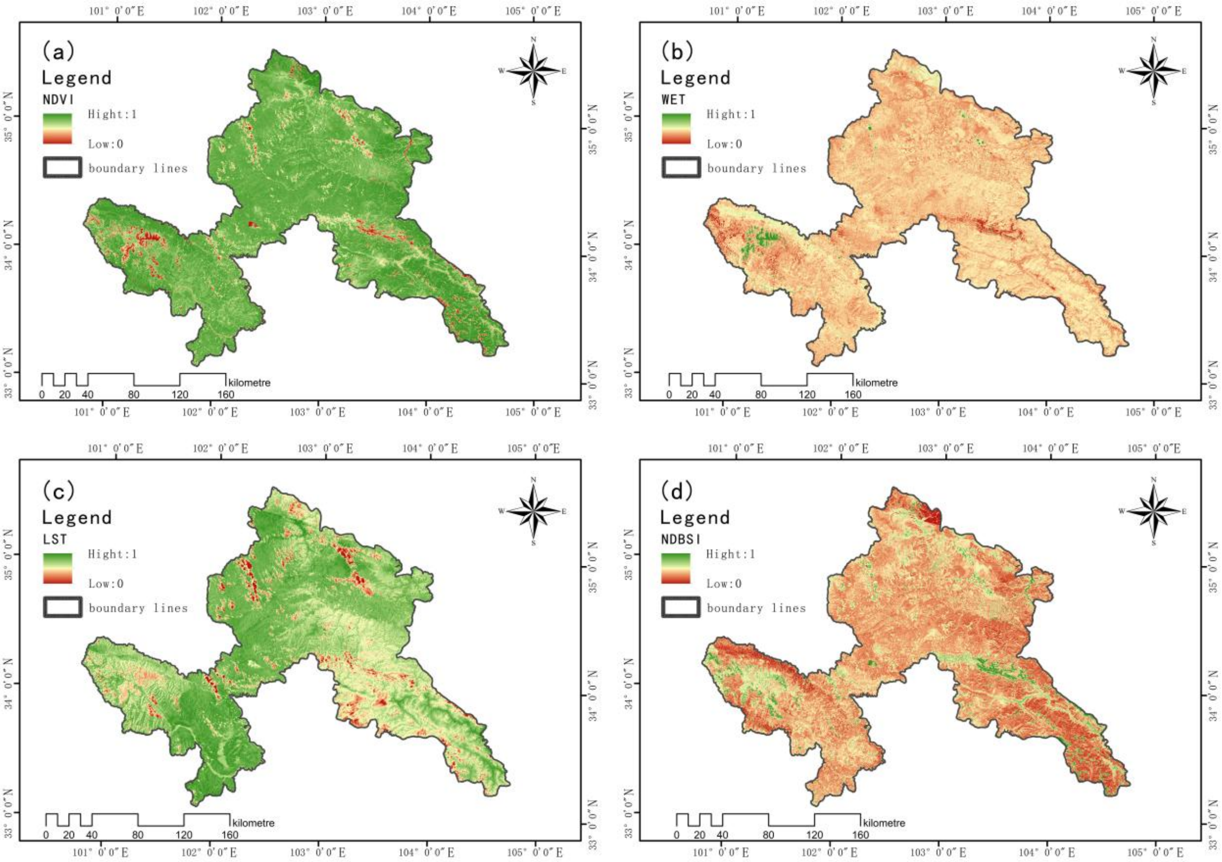

Figure 3 | (a) NDVI index (b) WET index (c) LST index (d) NDBSI index

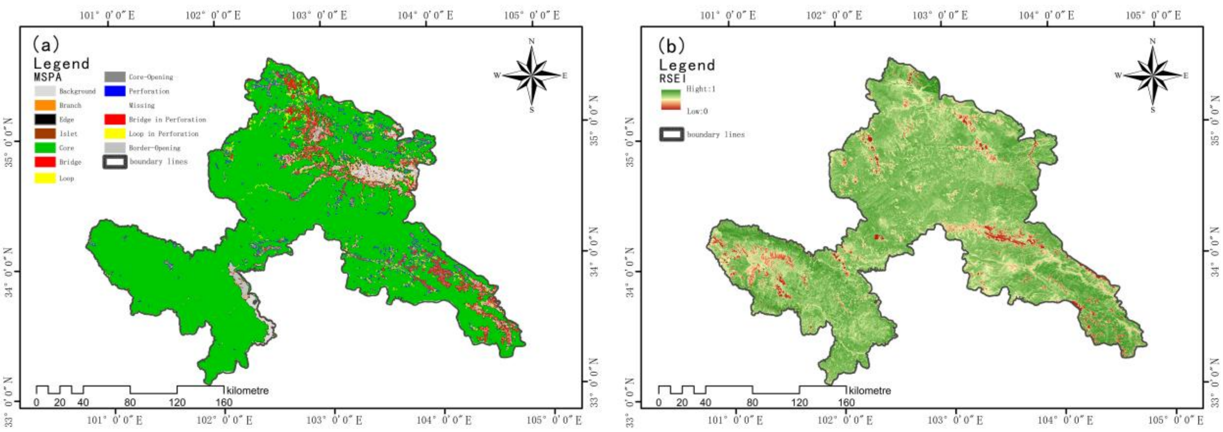

Figure 4 | (a) MSPA analysis (b) RSEI analysis

regions is worse than that of western regions, which is the reason for human activities and development.

4.1.3. Comprehensive Source and Comprehensive Source Point

The obtained MSPA data and RSEI data were reclassified in GIS respectively, and the reclassified data were calculated in the raster calculator with the weight of 0.5 each to obtain the comprehensive data, as shown in FIG.5 (a) below. The obtained comprehensive data was raster first. On the one hand, the patches were sorted in descending order; on the other hand, patch connectivity analysis was carried out with the Conefor plug-in, and patches with an area larger than 100Km2 and strong connectivity were selected as the integrated ecological source. The centroid of each source was selected as the ecological source point and numbered. A total of 38 ecological source points were selected, as shown in Figure 5 (b).

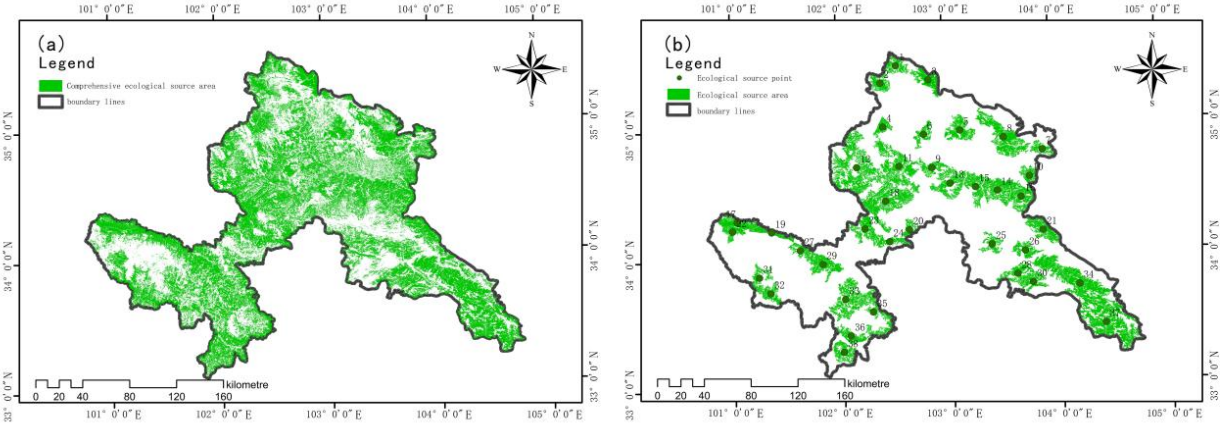

Figure 4 | (a) comprehensive source analysis (b) comprehensive source analysis

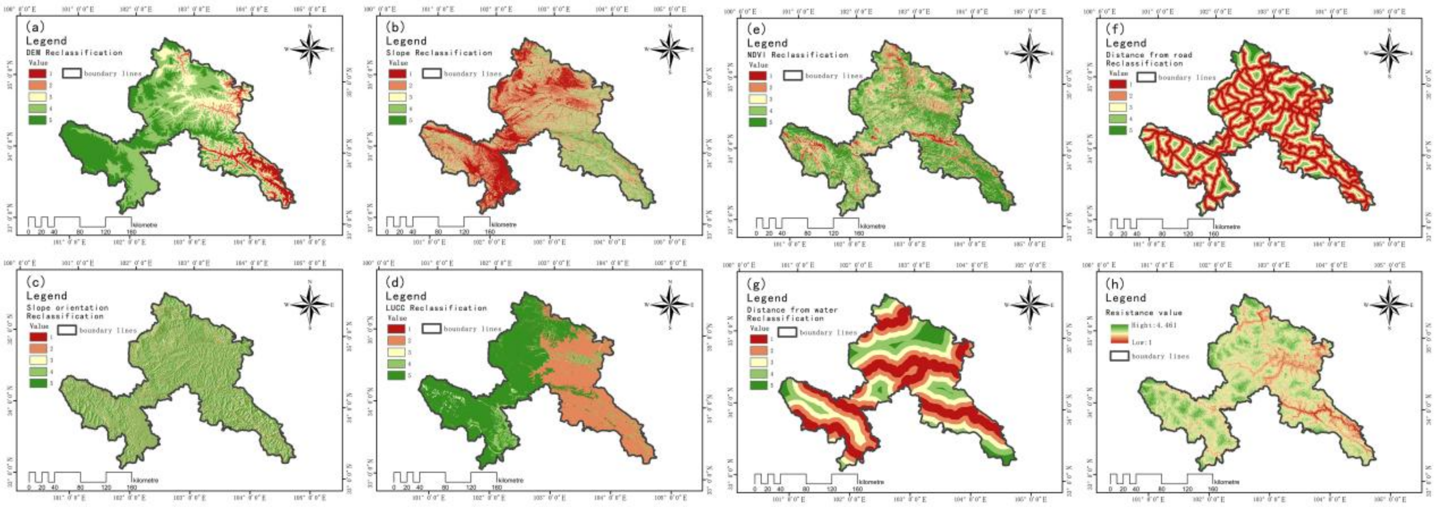

Figure 6 | (a) elevation resistance value (b) slope resistance value (c) slope resistance value (d) LUCC resistance value (e) NDVI resistance value (f) Distance from road resistance value (g) distance from water body resistance value (h) comprehensive resistance value

4.2. Construction of Ecological Resistance Surface

The seven resistance surface single factors mentioned in the research method are first cut to the same range size, resampling resolution is 30M, then unified reclassification is carried out, and finally the comprehensive resistance surface is obtained by superposition according to the weights, as shown in Figure 6.

As can be seen from Figure 6, the high-resistance area is mainly distributed in the east of the study area, which is greatly affected by the traffic network and other construction land. In addition, the area with high elevation and slope has rough terrain, which will increase the difficulty of species migration and ecosystem service flow. Low resistance in the western region, due to high vegetation cover and better ecological connectivity, is less resistance to the flow of species and ecosystem services.

4.3. Ecological Corridor and Key Point Identification

4.3.1. Ecological Corridor Identification

Linkage Mapper was used to identify and draw the lowest-cost route between ecological source points. As shown in Figure 7 (a), the ecological flow path mapped 96 ecological corridors, connecting the whole Gannan. The length of the ecological corridor is between 9.66 and 257.68km, and the total length is 5221.39km. The ecological corridors in Gannan are mainly distributed in the central and western regions, and the ecological source patch density in these regions is relatively high. These corridors realize the connectivity of the ecological source areas of the

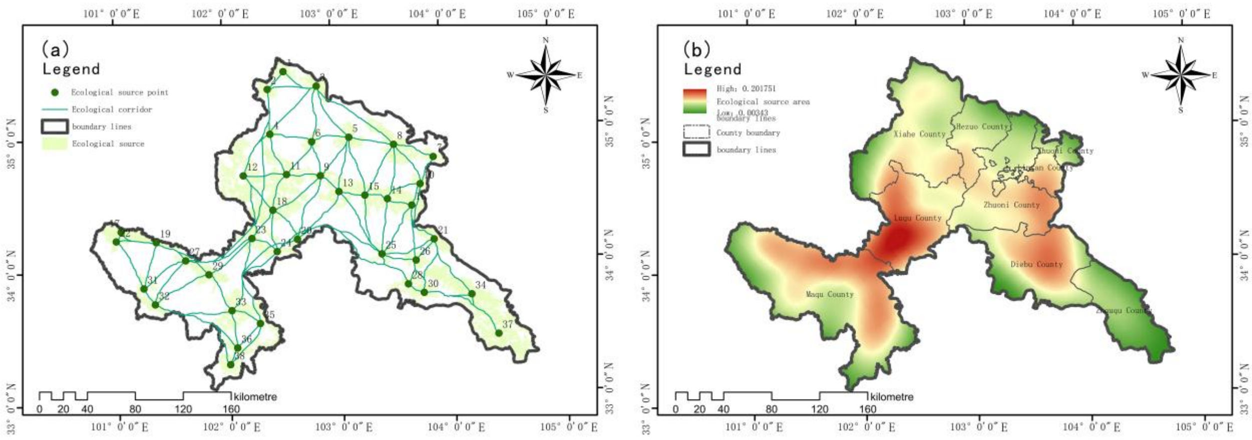

Figure 7 l (a) Ecological corridor analysis diagram (b) kernel density analysis diagram of ecological elements

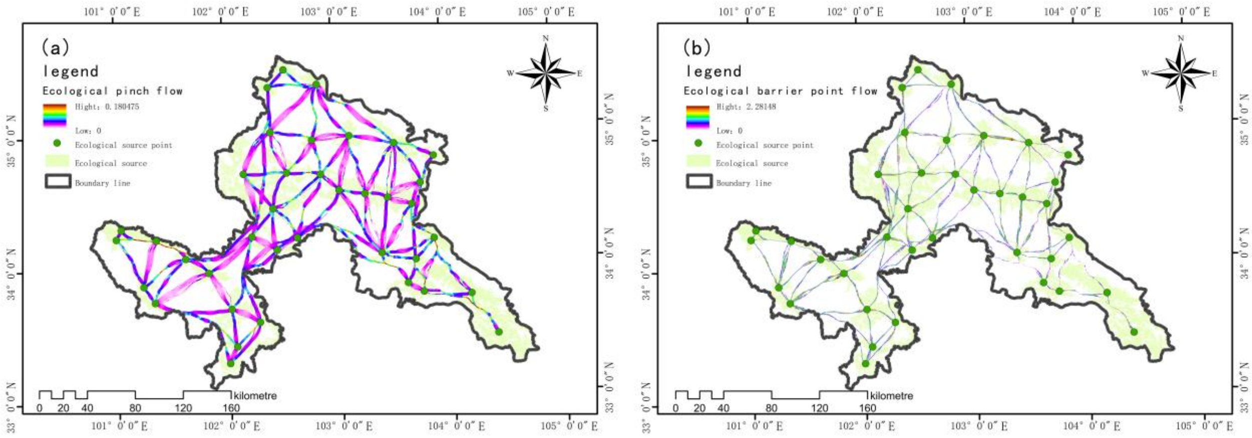

Figure 8 l (a) Ecological pinch point analysis diagram (b) ecological barrier point analysis diagram

whole city, successfully ensuring that each source area has at least one corridor connection, and forming a network loop. On the whole, the ecological corridor is relatively evenly distributed in the whole city.

The kernel density analysis of ecological source points and ecological corridors was carried out respectively, and then the two were assigned a weight of 0.5 respectively for superposition to obtain the kernel density analysis diagram of ecological elements, as shown in Figure 7 (b) below. In this way, the kernel density of different counties in the urban ecological source points was different, which was the ecological basis for the future development of different types of counties.

4.3.2. Ecological Pinch Identification

Ecological "Pinch point" is based on the "all to one" model of Pinch point Mapper tool, and 20km is selected as the weighted distance of corridor cost to obtain the value of corridor distribution current density, as shown in FIG. 8 (a) below. The identification of "pinch points" in the minimum-cost channels can often serve as a "stepping stone" role in the ecological network to prioritize the protection of these areas that are important for the connectivity of the study area and deserve to be protected.

4.3.3. Ecological Barrier Point Identification

The Barrier Mapper function of Linkage Mapper was used to identify the obstacle point, and the detection radius of 50-500m and step length of 50m were combined with the actual result to select 200m gradient as the most reasonable generation radius in this study, as shown in FIG. 8 (b) below.

4.3.4. Ecological Break Point Identification

In this study, the overlapping points of national highways, expressways and ecological corridors are identified as ecological "breaking points". As an important transportation infrastructure, the construction and operation of expressways have a significant impact on the surrounding environment, including not only the destruction of ecological environment, the reduction of biodiversity, and the fragmentation of landscape, but also the impact on ecosystem functions. Such as the blocking of animal migration path, loss of ecological niche and so on. The function of the ecological corridor is to promote the communication between species and the health of the ecosystem, and to ensure the integrity of the ecosystem. However, the existence of highways often becomes a "breaking point" in the ecological corridor, which hinders the movement of wildlife and the progress of ecological processes.

4.4. Ecological Security Pattern Identification

4.4.1. Ecological Corridor Classification

The method of quantitative analysis of ecological corridor classification in this study is based on the ratio of cost-weighted distance to the minimum cost path, which can help researchers evaluate and compare the quality and function of different ecological corridors. An index reflecting the connectivity of ecological corridors can be obtained. The smaller the ratio, the smaller the gap between the actual moving distance and the minimum-cost path, indicating that the stronger the connectivity of the ecological corridor, the fewer barriers for species to migrate within it. Among them, the ratio between 1-1.06 is the key ecological corridor, the ratio between 1.06-1.1 is the important ecological corridor, and the ratio greater than 1.1 is the general ecological corridor. The specific results are shown in FIG. 9 (a) below. Among them, there are 10 important ecological corridors, 61 key ecological corridors and 25 general ecological corridors. In the future, the protection and restoration strategies for ecological corridors are different. The general corridors with the least connectivity should be repaired with emphasis, while the important ecological corridors with the strongest connectivity should be protected and maintained. It can be seen from the figure that important ecological corridors are located in areas with relatively high resistance values, such as Diib County and Xiahe County, which have relatively flat terrain and mild climate conditions, providing important migration channels. General ecological corridors are located in areas with high resistance values such as Maqu County, where the terrain is different and the connectivity is weak. In addition, it is worth noting that there are many general ecological corridors in Zhouqu County, but the resistance value in Zhouqu County is small, which is related to the reason why natural disasters are distributed most in Zhouqu County.

4.4.2. Ecological Key Point Extraction

The ecological key points mentioned here refer to the ecological break points of ecological pinch points and ecological obstacle points.

Firstly, the ecological pinch points were divided into five categories by the natural fracture method to extract the current value. The area with the highest value of the fifth category was taken as the ecological pinch points. The consensus was 908 spots with a total area of 47.82km2, the largest ecological pinch point area was 6.350502km2, and the minimum ecological pinch point area was 0.000576km2. Ecological pinch points were obtained on the basis of an analysis within a buffer zone of 1000 and 2000 m, as shown in Figure 9 (b) below.

Secondly, for ecological obstacle points, the generated obstacle areas are divided into three levels using the natural breakpoint method, including first-level obstacle points, second-level obstacle points and third-level obstacle points, as shown in FIG. 9 (c) below. The cumulative current recovery value was divided into 698 first-order obstacle points, 550 second-order obstacle points and 550 third-order obstacle points, with a total area of 6105.36km2, accounting for 13.57% of the study area. The obstacle points are mainly distributed in Maqu County, Luqu County, Zhuoni County and Lintan County in Gannan Prefecture. The number of Grade I obstacle points in Luozhilu, Gahai Lake and Guomeng Wetland reserve is large and the area is large. Therefore, ecological restoration should be strengthened in the surrounding areas. Secondary and tertiary obstacle points are the supplement of primary obstacle points, which mainly appear near the source area and inside the ecological corridor. The spatial structure is distributed in groups, and the restoration is difficult and the effect is relatively slow. Long-term improvement and optimization plans need to be formulated.

Thirdly, for ecological "break points", the consensus identifies 66 ecological "break points", of which 8 intersect with highways and 58 intersect with national highways, as shown in Figure 9 (d) below. Xiahe County and Hehe City have a large number of "break points" formed by cutting expressways. Overall, there are 19 "break points" in Xiahe County, 12 "break points" in Luqu County, 9 "break points" in Zhuoni

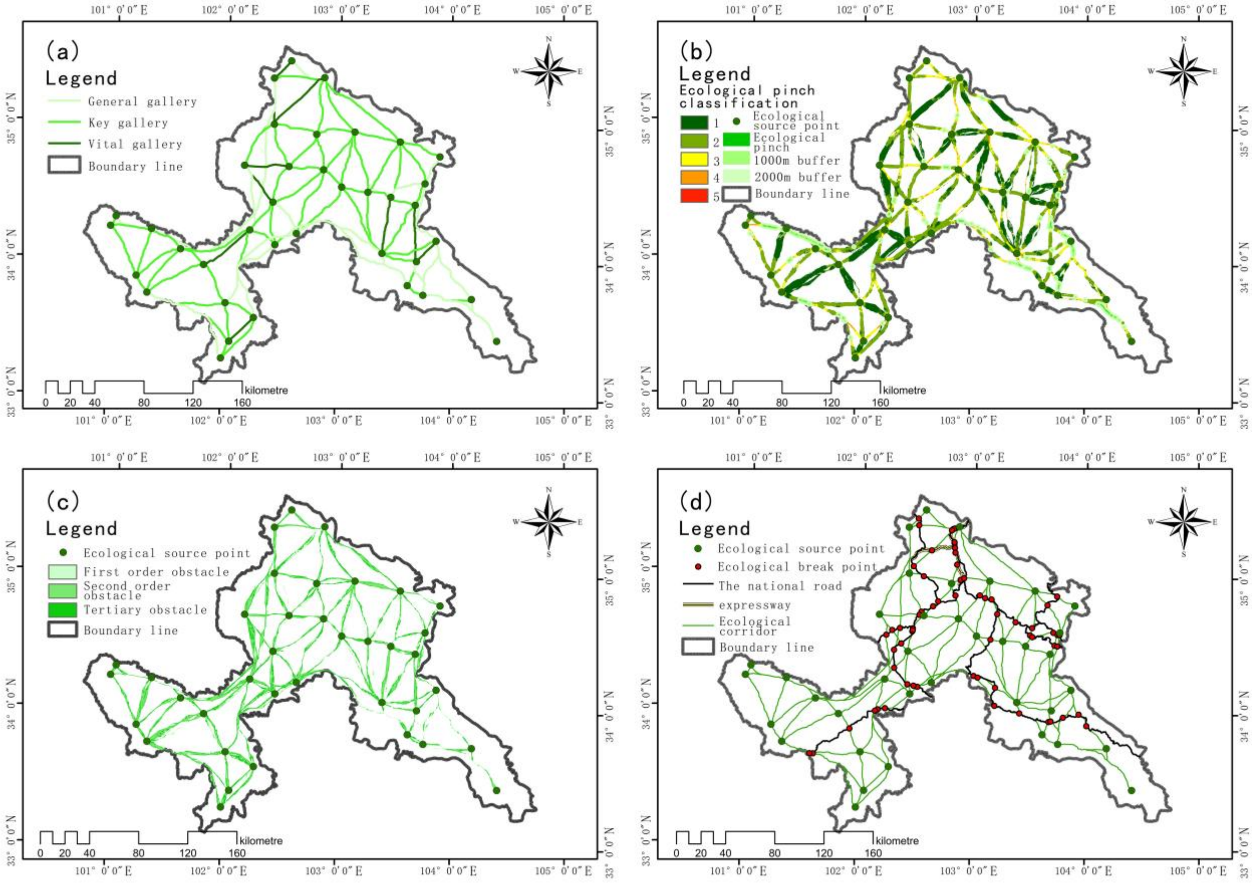

Figure 9 | (a) classification of ecological corridor (b) extraction of ecological pinch points (c) extraction of ecological barrier points (d) extraction of ecological break points

County and Diebe County, 8 in Lintan County, 6 in Maqu County, 2 in Hehe City and 1 in Zhouqu County. The "break point" has a great impact on ecological transmission, and most of the traffic arteries and ecological corridors are vertically distributed, so it is difficult to find other alternative points near the corridors, which seriously hindering the ecological flow. Xiahe County, Luqu County, Zhuoni County and Dibu County have a large number of fracture points, among which Xiahe County has 19 "fracture points". Xiahe County is in the north of Gannan Prefecture, and has close material exchanges with peripheral cities, and the traffic quantity is developed, which increases the number of ecological fracture points.

4.4.3. Construction of Ecological Security Pattern

The ecological security pattern is constructed by combining the ecological corridors classified by ecological pinch points, ecological barrier points and ecological break points analyzed above, as shown in Figure 10 (a).

Combined resistance surface data and ecological remote sensing index were used to partition the ecological security pattern. The ecological resistance surface reflects the impeding effect of different landscapes on ecological processes, while the ecological remote sensing index provides a rapid assessment of regional ecological environment quality. By combining these two methods, the regions of low security, medium security and high security can be more accurately divided, as shown in Figure 10 (b). There are three types of ecological security pattern, in which the low security pattern refers to the area with poor ecological status and serious obstruction of ecological process, including the area with high ecological resistance and low RSEI value. In the middle security pattern, the region requires certain ecological restoration and management measures, and the ecological resistance and RSEI value are at a medium level. The high security pattern area refers to the area with good ecological status, smooth ecological process, low ecological resistance and high RSEI value.

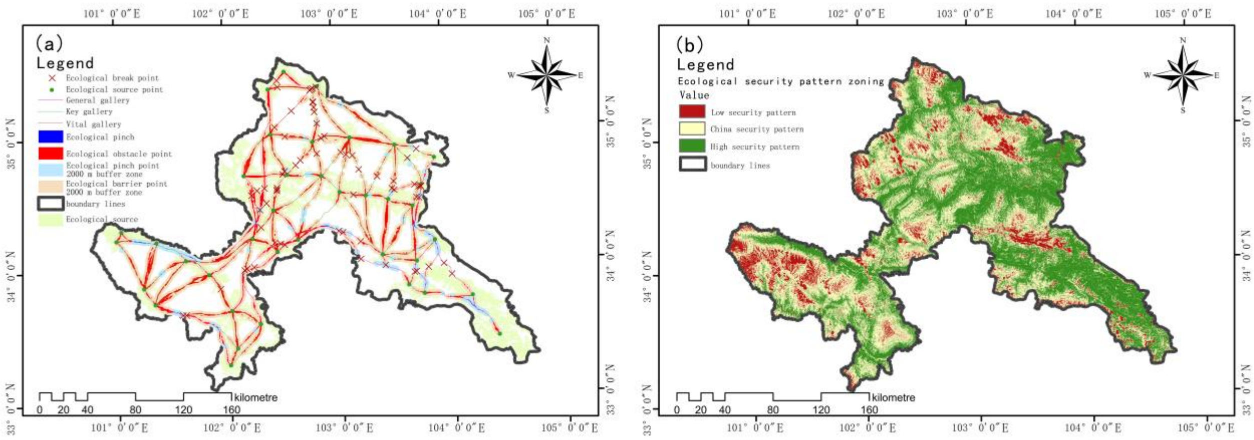

Figure 10 | (a) Ecological security pattern of Gannan Prefecture (b) ecological security zoning

4.5. Ecological Problem Identification

4.5.1. Building an Ecological Issues Index (EPI)

The concept of "mountains, rivers, forests, fields, lakes, grass and sand are a community of life" emphasizes the interdependence and integrity of these natural elements, and requires us to adopt a systematic governance approach when carrying out ecological protection and restoration, taking into account the relationship between various elements as a whole, and achieving the goal of harmonious coexistence between man and nature.

In the construction of China's ecological civilization, each word "mountains, rivers, forests, fields, lakes, grass and sand" represents a specific natural element or ecosystem. Based on the practical needs of practicing green mountains and mountains as gold and silver mountains and preventing and resolving ecological risks, this paper starts from the concept of "mountains, rivers, forests, fields, lakes, grass and sand are a community of life", and constructs the diagnostic indicators of ecological problems of "mountain - water - forest - field - lake - grass - sand", as shown in Table 4.

For the mountain ecosystem in the index system of "mountain - water - forest - field - lake - grass - sand", vegetation coverage and natural disaster distribution kernel density were selected, and the kernel density of natural disaster mainly included landslide, debris flow, collapse, slope and other disasters related to the mountain. In the water ecosystem, the distribution of annual precipitation is selected. The northerly slope of Gannan aggravates the decline of precipitation from south to north. Therefore, the annual precipitation in southern Gannan can reach more than 600 mm, while that in central and northern Gansu is less than 200 mm. For forest ecosystem and grassland ecosystem, the net primary productivity of forest land and the primary productivity of grassland were selected respectively. Farmland ecosystem is an index of cultivated land fragmentation. The boundary density index represents cultivated land fragmentation, and the ratio of cultivated land patch circumference to cultivated land area is used. The greater the ratio of the two, the higher the degree of cultivated land is divided by boundary. The lake ecosystem was represented by the water conservation of Gannan Prefecture. The ecosystem of sandy land was represented by soil erosion index.

According to the eight indicators in the above table, all of them are first cut to the same range size, the resampling resolution is 30M, and then uniformly reclassified into five categories. For the three factors such as forest land degradation degree, grassland degradation degree and cultivated land fragmentation degree, the empty value is assigned as 1, in order to facilitate the subsequent calculation of comprehensive ecological problem data with the Ecological problem index (EPI) formula. Among them, the reclassification of eight indicator factors is shown in Figure 11 below.

4.5.2. Territorial Ecological Problems Identification Zone

According to the Ecological Problem Index (EPI) formula, combined with the weights of eight index factors, the comprehensive ecological problem data was calculated, as shown in Figure 12 (a). Then, the obtained comprehensive data are reclassified into four categories, as shown in Figure 12 (b). The larger the regional value of ecological problems, the more prominent the ecological problems. When

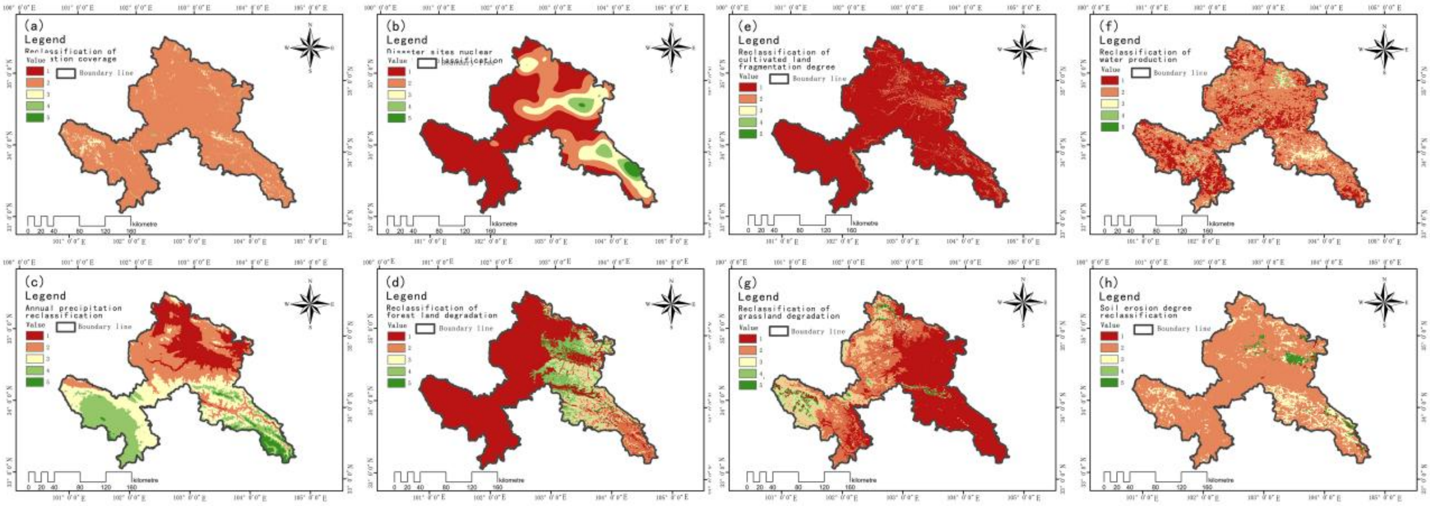

Figure 11 | (a) Reclassification of vegetation coverage (b) Reclassification of core density of disaster sites (c) reclassification of annual precipitation (d) reclassification of woodland degradation (e) reclassification of cultivated land fragmentation (f) reclassification of water yield (g) reclassification of grassland degradation (h) reclassification of soil erosion

Table 4 | Diagnostic index system of ecological problems of "mountain-water-forest-field-lake-grass-sand"

Repair object	Ecosystem	Ecological problem	Index name	Weight	Data processing	Nature	Assign				
							1	2	3	4	5
mountain	Mountain ecosystem	Vegetation thinning	Vegetation coverage	0.17	NDVI	-	0.8-1	0.6-0.8	0.3-0.6	0.1-0.3	0-0.1
		Geological disaster	Disaster distribution map		Nuclear density analysis of disaster site distribution map	+	0-0.01	0.01-0.03	0.03-0.06	0.06-1	＞1
water	Aquatic ecosystem	Extreme precipitation	Annual precipitation distribution	0.14	Annual precipitation distribution map	+	＜550	550-580	580-620	620-660	＞660
forest	Forest ecosystem	Forest degradation	Forest degradation degree	0.15	Woodland NPP data + woodland fragmentation	+	＞0.7	0.6-0.7	0.5-0.6	0.4-0.5	＜0.4
field	Farmland ecosystem	Farmland fragmentation	Cultivated land fragmentation	0.15	Cultivated land distribution data	+	＜0.006	0.006-0.015	0.015-0.03	0.03-0.09	＞0.09
lake	Lake ecosystem	Water shortage	Water conservation capacity	0.13	Yield data	-	＞2000	1900-2000	1800-1900	1700-1800	＜1700
grass	Grassland ecosystem	Grassland degradation	Grassland degradation degree	0.15	Grassland NPP data + grassland fragmentation	+	＞0.4	0.35-0.4	0.3-0.35	0.25-0.3	＜0.25
sand	Sandy land ecosystem	The land has been severely eroded	Soil erosion degree	0.11	Soil erosion degree	+	No obvious erosion	Slight erosion	Mild erosion	Moderate erosion	Intense erosion

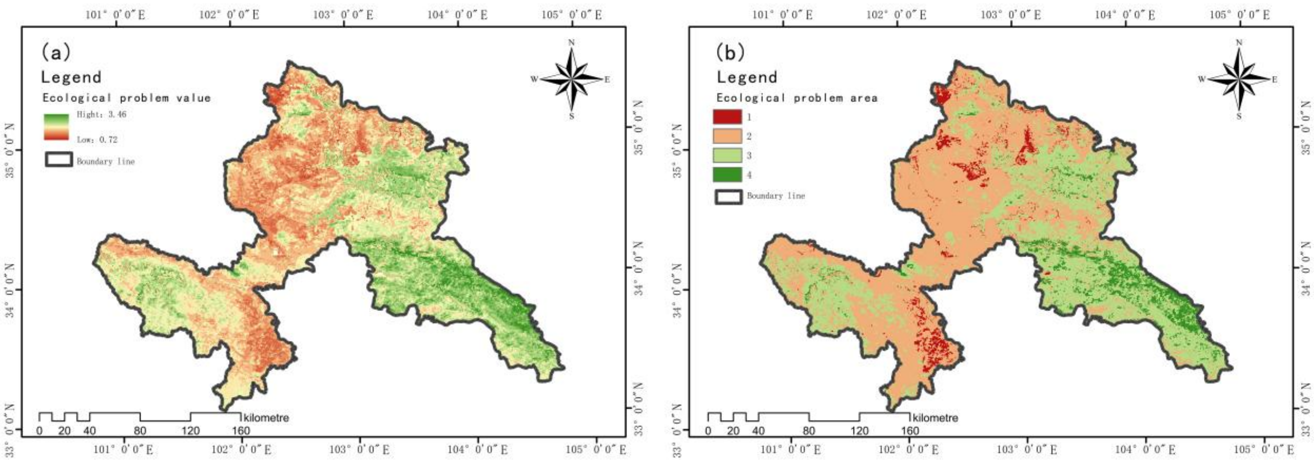

Figure 12 | (a) Integrated ecological issues (b) Ecological issues regionalization

0.72≤EPI<1, it is classified as 1, which belongs to the critical maintenance area. When 1≤EPI<1.5, it is classified as 2 and belongs to the critical control area. When 1.5≤EPI<2, it is classified as 3 and belongs to the key lifting area. When 2≤EPI<3.46, it is classified as 4 and belongs to the key repair area. It can be seen from the figure that the most ecological restoration areas are in Zhouqu County, Diib County and Maqu County.

First of all, Zhouqu County, as an area with frequent natural disasters, the wide distribution of its ecological restoration area is closely related to the topography and climate conditions of the area. Zhouqu County's complex terrain, mountainous and steep, coupled with the changeable climate, these factors together lead to frequent geological disasters, such as landslides, debris flows and so on. These disasters not only destroy the local ecological environment, but also pose a threat to the life and safety of residents. Therefore, ecological restoration efforts focus on stabilizing the terrain, restoring vegetation, reducing soil erosion, and improving the resilience of ecosystems to natural disasters.

Secondly, the ecological restoration area in Dibe County is related to its specific geographical location and ecological environment. Dibe County is located in the transition zone between plateau and mountain, where the ecosystem is relatively fragile and vulnerable to climate change and human activities. Ecological restoration efforts focus on restoring and protecting local forest ecosystems, as well as improving soil and water conservation. In addition, Dibe County needs to take measures to reduce the negative impact of agricultural activities on the ecosystem, such as overgrazing and land degradation, so as to maintain the ecological balance and biodiversity.

Third, although the geographical location of Maqu County is relatively high, the ecological resistance value is relatively low, but this does not mean that the ecological restoration work is not important. The ecological environment of Maqu County is good, which provides a good basis for ecological restoration. The distribution of restoration areas is more focused on improving ecosystem services, such as water conservation capacity and biodiversity conservation.

4.6. Ecological Coupling Result

The data of ecological problems and the data of ecological security pattern were analyzed in different regions, and the average value of each data was distributed to 99 townships in Gannan Prefecture, as shown in Figure 13.

It can be seen from the figure that the regions with high ecological problem value in Gannan are mainly distributed in Diabe County, Zhouqu County and Lintan County. The pattern of high ecological security is distributed in four regions: Zhouqu County, Zhuoni County, Lintan County and Hehe City. The paradox is that Zhouqu County and Lintan County have high ecological problem value and high ecological security pattern. Because these areas have a high ecological sensitivity, easy to be affected by natural factors (Zhouqu debris flow) and human activities, leading to more prominent ecological problems. At the same time, it is precisely because of historical ecological events in these regions that the ecological protection awareness of local governments and residents has been enhanced, prompting them to invest more resources and efforts in ecological protection and

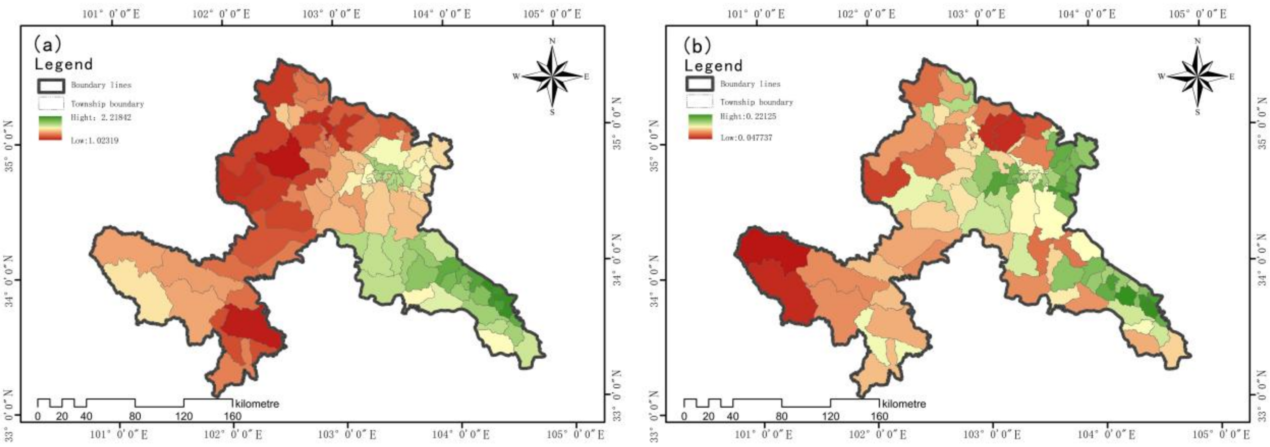

Figure 13 l (a) Regional statistics of ecological problems (b) regional statistics of ecological security pattern

restoration, thus forming a high ecological security pattern.

In order to further study the interaction relationship between ecological problems and ecological security pattern, the two are coupled, as shown in Figure 14. Two coupling methods are adopted in this paper. The first is the coupling coordination model, which identifies the coordination degree of ecological problems and ecological security pattern in each township and identifies the synchronization before them. The second is spatial coupling superposition, which superimposes ecological problems and ecological security pattern.

In combination with Figure 14 (a) and Table 5, it can be found that only 8 townships in Gannan are within the scope of imbalance, while the others are within the scope of coordination, indicating that the identification of ecological problems in Gannan is largely consistent with the identification of ecological security pattern. But Thongchin street is seriously dysfunctional, and Ganga Town and Kecai Town are among the seven towns on the verge of dysfunctional towns that need different strategies and measures.

There are six types of spatial superposition results, the values are 2, 3, 4, 5, 6 and 7 respectively, as shown in Table 6.

5. Discussions

5.1. Ecological Space Restoration Strategy Proposed

5.1.1. Ecological Point Strategy Is Proposed

a. Ecological break point

In this study, the break points are divided into highway break points and national highway break points, so targeted strategies are proposed. First, for the ecological break points of the highways, the restoration strategy focuses on the design and implementation of dedicated wildlife passageways, such as overpasses or underpasses, and the planting of native vegetation on both sides of the highways to form natural ecological corridors. In addition, the effectiveness of the ecological corridor is ensured through the installation of isolation facilities and regular monitoring management. These measures aim to reduce animal-vehicle conflict while improving ecological connectivity and protecting and promoting biodiversity. Secondly, for the ecological break points of national highways, the strategy focuses more on reducing the speed limit and optimizing the road design to reduce the impact on the ecologically sensitive areas. Implementing ecological compensation measures, such as afforestation near affected areas, to balance ecological losses. In addition, through traffic control and community participation, the construction and maintenance of ecological corridors are strengthened. At the same time, multi-functional green Spaces and intersectoral cooperation mechanisms, as well as continuous monitoring and evaluation, will be established to ensure the long-term benefits of ecological corridors in conserving biodiversity and providing ecosystem services.

b. Ecological pinch

When the ecological pinch points are superimposed with the integrated resistance surface, the ecological pinch points are located with less resistance and easy to migrate species, so it is necessary to focus on protection and management of these areas.

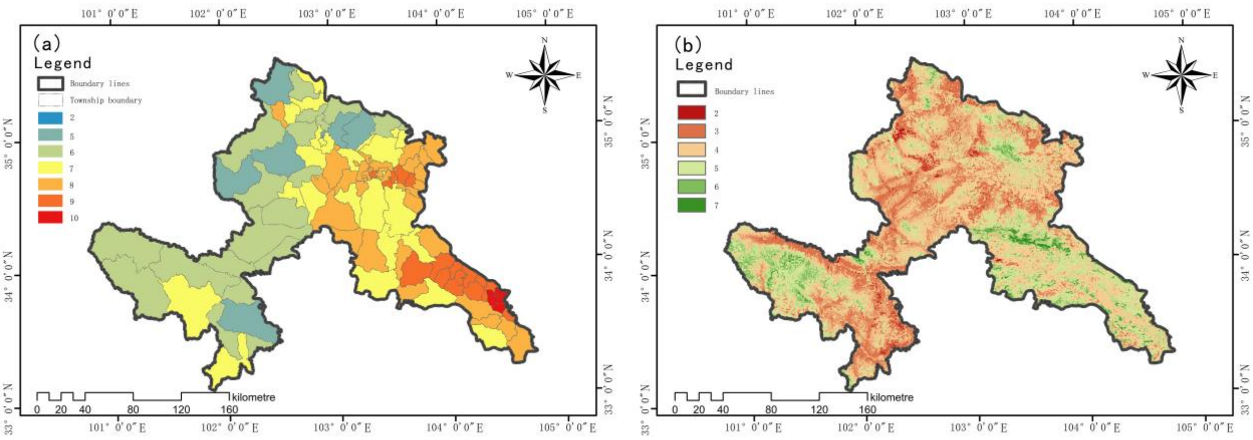

Figure 14 | (a) ecological coupling level (b) ecological coupling zone

Superimposed with land use classification and remote sensing images, the land types located in the pinch points are mainly woodland, grassland and water bodies. Some pinch points have high vegetation coverage, and these areas are extremely sensitive when subjected to certain external interference activities. These areas need to be protected and managed to prevent natural disasters such as soil erosion.

The ecological pinch area larger than 0.5km2 was selected as the key protection area, and a buffer area of 2000 meters was set around it. A total of 20 spots were numbered, as shown in Figure 16. Among them, 13 sites are located in the ecological source area (2, 3, 4, 5, 6, 7, 8, 11, 12, 13, 14, 15, 16), and 7 sites are not located in the ecological source area (1, 9, 10, 17, 18, 19, 20).

For ecological pinch points located in ecological source areas, conservation strategies should focus on ecological monitoring and restoration, establishing conservation buffer zones to reduce human disturbance, maintaining ecological connectivity to ensure species migration, protecting water sources, using areas for scientific research and education, and encouraging community participation and sharing in ecological conservation benefits. These measures help to maintain the natural state and ecological function of the ecological pinch, while promoting harmonious symbiosis with the surrounding ecosystem. For ecological pinpoints that are not located in ecological

Table 5 l Coupling coordination degree of towns and villages in Gannan Prefecture

Coupling coordination level	Degree of coupling coordination	Number of townships	Specific township
2	Severe disorder	1	Tongchin street
5	Borderline disorder	7	Ganga Town, Kocai Town, Amugohu Town, Manzhima Town, Janmukir Street, Sogaimanma Town, Sogaidoma Township
6	Forced coordination	19	Kangduo Township, Madang Town, Tanggaang Township, Jicang Township, etc
7	Primary coordination	22	Wanmao town, scoop wa Tu Township, Kailchin town, Chagai Township, etc
8	Intermediate coordination	29	Narang Town, Niba Town, Azitan Town, Zagulu town, etc
9	Good coordination	16	Liulin Town, Lijie town, Hanban town, Basang town, Fengdiai town, etc
10	Quality coordination	5	Guoye Town, Dongshan Town, Jiangpan Town, Nanyu Township, Dachuan town

Table 6 | Superimposed data table of ecological problems and ecological security pattern in Gannan Prefecture

Superimposed result	Area (km2)	Sectional implication	Partition name
2	790.75	High - maintenance area	Ecological protection area
3	10623.57	Medium - maintenance area, high - control area	Ecological maintenance area
4	19871.56	Medium - control area, high - lifting area, low - maintenance area	Ecological development area
5	8510.18	Medium - lift area, low - control area	Ecological control area
6	2797.62	Low-lift area, medium-repair area	Ecological enhancement area
7	598.25	Low - repair area	Ecological restoration area

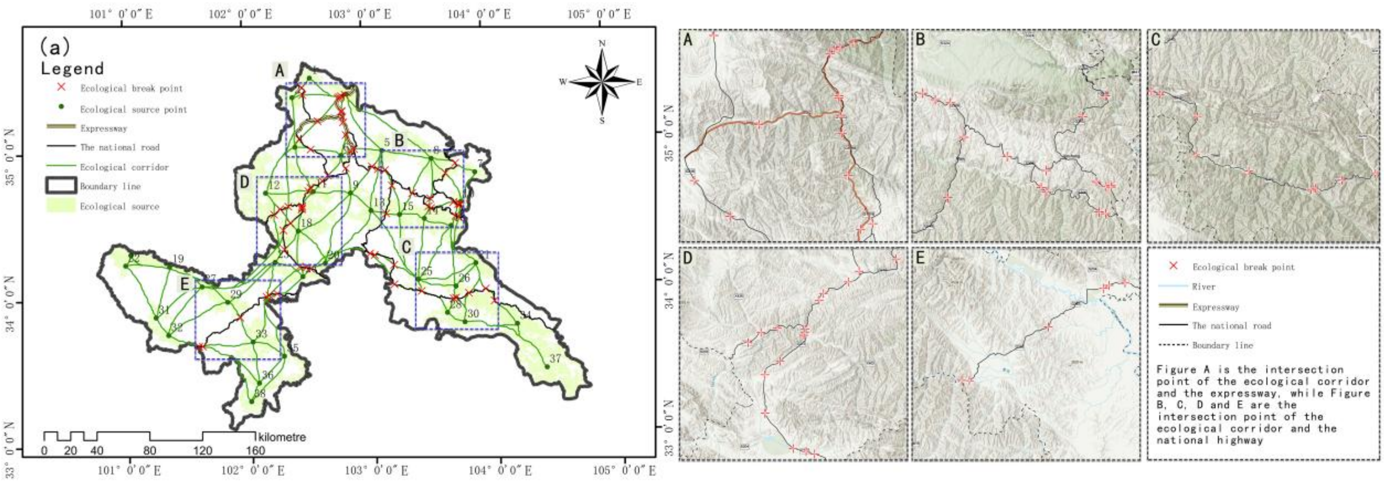

Figure 15 | Ecological break point strategy

sources, conservation strategies need to include environmental impact assessments to prevent potential damage, ecological risk management and compensation to mitigate the impact of development activities, ecological restoration works to restore damaged areas, rational land use planning to avoid improper development, stronger enforcement of laws and regulations to curb vandalism, and public awareness to increase social participation. Promoting cross-regional cooperation to achieve broader ecological protection. These strategies are designed to ensure that these key ecological areas receive appropriate attention and protection, even if they are not directly located within the ecological source area.

c. Ecological obstacle point

According to the superposition analysis of ecological barrier points and comprehensive resistance surface, the barrier points are mostly distributed in the positions with higher resistance values, which is not conducive to the connectivity of landscape pattern. Superimposed with land use classification and remote sensing images, the obstacle points are mainly located on construction land, forest land, grassland and cultivated land, and the first-order obstacle points are mostly distributed on construction land, which has great interference from human activities and obstructs material exchange.

In this study, a total of 48 patches with ecological obstacle points larger than 10km2 were selected. A buffer zone of 2000 meters was made around them, and the buffer zones were connected into pieces to number the remediation areas, with a total of 22 numbered areas, as shown in Figure 17. Strategies are classified according to the number of ecological source points in the region shown in the figure. There are 4 sites without source points: 5, 13, 15 and 17; 10

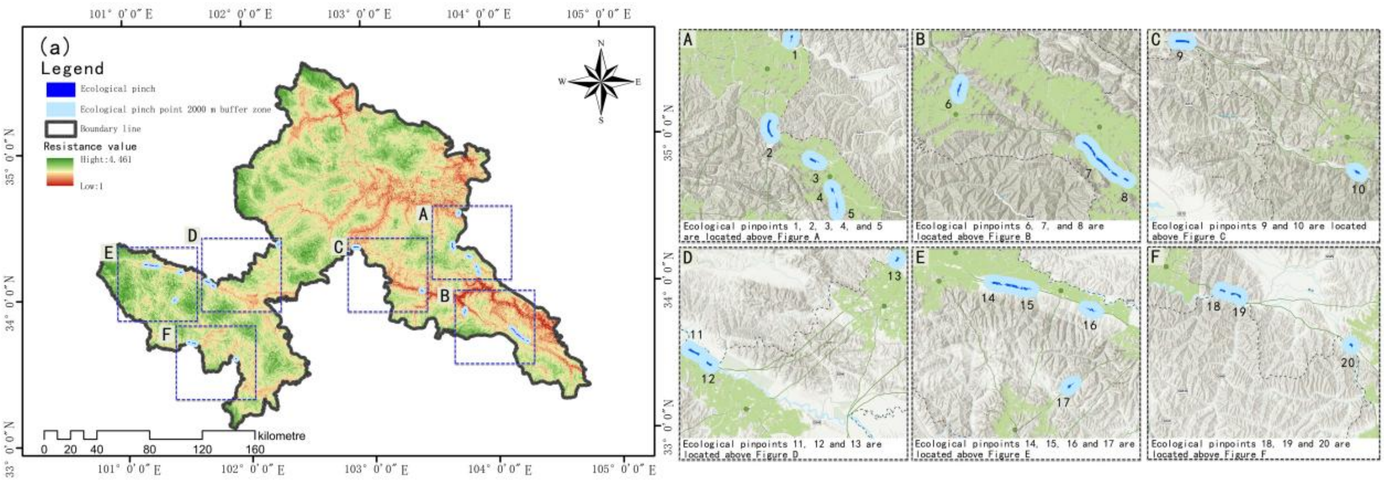

Figure 16 | Ecological pinch strategy

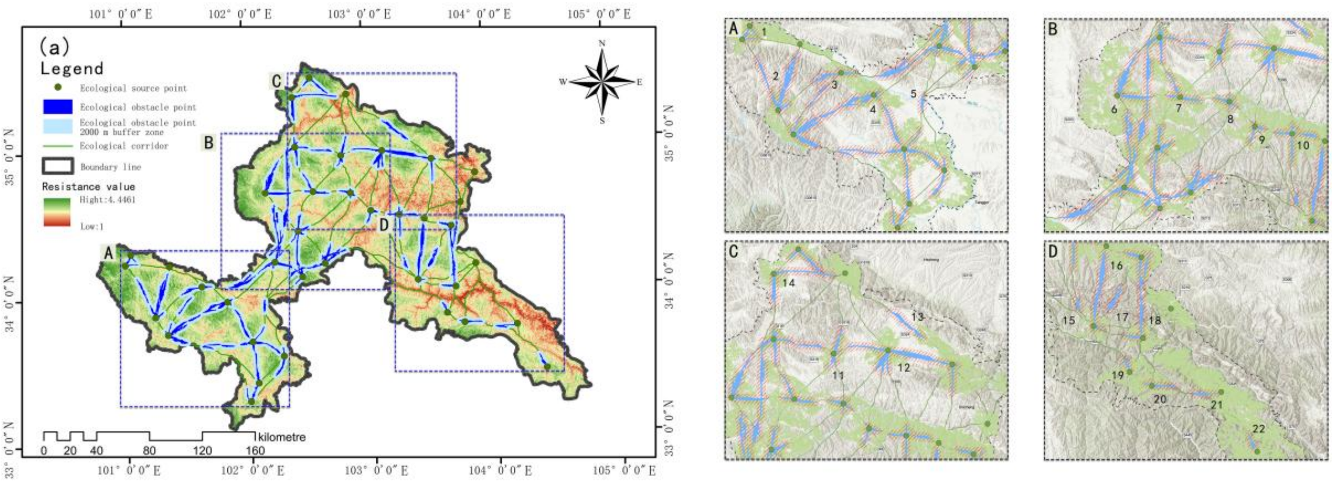

Figure 17 | Ecological barrier point strategy

sites with 1 source point: 7, 8, 9, 10, 11, 12, 19, 20, 21 and 22; and 6 sites with 2 source points: 1, 2, 3, 14, 16 and 18. The ones with 3 or more are 4 and 6.

In the face of non-ecological source points in Gannan (No. 5, 13, 15, 17), the strategy should focus on ecological reconstruction and vegetation restoration. Specific measures include the selection of cold-tolerant and drought-tolerant native plants for large-scale planting, as well as the establishment of long-term ecological monitoring sites to regularly assess the restoration effect, and ensure that the ecosystem gradually recovers and ADAPTS to the local alpine environment. For obstacle sites with a single ecological source point (numbers 7, 8, 9, 10, 11, 12, 19, 20, 21, 22), the strategy should strengthen source point protection and expand ecological restoration. By establishing ecological buffer zones around obstacle points, limiting possible disturbance activities, while building ecological corridors, enhancing biodiversity and ecological connectivity, and promoting safe species migration and gene flow. In the face of obstacle points with two ecological source points (numbers 1, 2, 3, 14, 16, 18), the strategy needs to optimize the ecological network structure. Through vegetation restoration and ecological engineering, the two source points are connected through an ecological corridor to form a more stable ecological network, while improving the ecological service functions of the obstacle points and their surrounding areas, such as enhancing carbon sink capacity and water conservation. For obstacle sites with three or more ecological source sites (numbers 4 and 6), integrated ecological planning is required. According to the ecological functions and geographical distribution of the source points, different ecological functional areas are divided, differentiated protection and management measures are implemented, priority is given to restoring the more vulnerable areas with high ecological value,

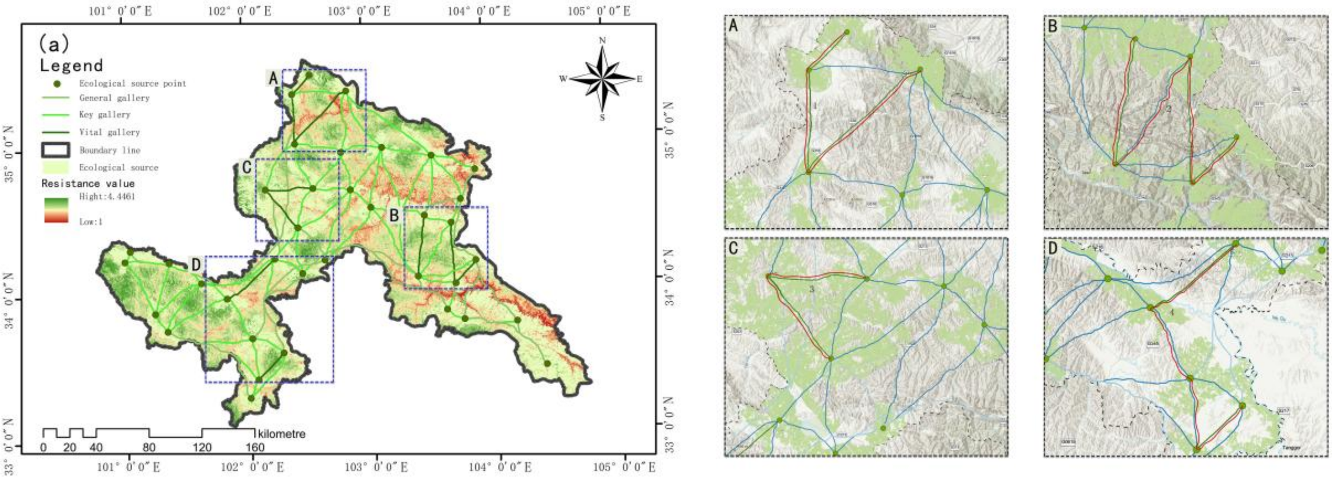

Figure 18 | Ecological corridor strategy

and ecological protection complexes are built to achieve the optimization and sustainable development of the entire ecosystem.

5.1.2. Ecological Line Strategy Proposed

In this study, 10 important ecological corridors were selected, but the 10 ecological corridors were widely distributed. Therefore, in order to further stabilize the role of ecological corridors, 10 corridors are formed into 4 ecological corridor groups, as shown in Figure 18. Among them, corridor group No. 1 and corridor Group No. 3 are connected by important corridors, corridor group No. 2 is a corridor group combined by adding a key corridor, and corridor group No. 4 is a corridor group combined by adding two key corridors, as shown in Figure 18.

According to the information of each corridor shown in Table 7 above, different strategies are given respectively. The No. 1 Ganga Town-Sangke Town-Quao Town ecological corridor group, given that it spans many roads and is dominated by grassland, the strategy should include limiting construction activities within a certain range on both sides of the road to reduce light and noise pollution; Add ecological signs and speed bumps to remind drivers of wildlife; At the same time, seasonal grazing bans are implemented to promote the natural recovery of grasslands, and grassland health conditions are regularly monitored. The No. 2 Muler Town-Dianga Town-Narang Town-Wangzang Town-Lazikou town-ecological corridor group, since it passes through many towns and mainly forests, the strategy should include formulating ecological connectivity planning among townships and increasing the biodiversity hotspots at the forest edge; Implement long-term forest ecosystem monitoring projects to assess ecological service functions; And promote sustainable forest management practices, such as selective logging and forest renewal. No. 3 Sangke Town - Kecai Town - Amuohu Town ecological corridor group, land use is mainly grassland and transverse across the river, the strategy should focus on the maintenance of river ecological flow, to ensure the health of river ecosystem; Implement the construction of riverbank vegetation buffer zone to reduce agricultural non-point source pollution; And carry out grassland ecological monitoring, rational planning of grassland utilization, avoid overgrazing. No. 4 Gahai Town-Eula Town-Manzhima Town-Zezhima ecological corridor group, the land use is wetland and grassland, across the Yellow River and the national highway, the strategy should include the establishment of wetland protection areas, limiting activities that may affect water quality; Set up ecological isolation zones and sound barriers along the national highway to reduce the disturbance to the wetland ecosystem; The value assessment of wetland ecosystem services should be carried out to raise public awareness of the importance of wetland protection.

5.1.3. Ecological Surface Strategy Is Proposed

According to the six regions divided into ecological problems and ecological security patterns, protection and restoration strategies are proposed for each region from a strategic perspective and specific strategic measures, and customized according to the characteristics of its ecological security pattern and ecological problems faced, so as to ensure that ecological protection and restoration work is scientific, reasonable and practical. To achieve the health of the ecosystem, the enrichment of biodiversity and the enhancement of ecological services.

According to the ecological problem identification and the ecological security pattern of the coupling of the seven districts, also for the township gives different strategies. For the seriously disordered area of Tongqin street, a comprehensive ecological restoration project should be started immediately, including pollution control and ecological reconstruction. At the same time, environmental supervision will be strengthened to ensure that all activities comply with ecological protection standards, and key ecological issues will be identified and prioritized through ecological risk assessment.

For areas on the brink of dysregulation, such as Ganga and Kecai towns, it is key to strengthen ecological monitoring in order to detect and respond to early signs of ecological degradation. Develop ecological conservation plans that focus on soil and water conservation and biodiversity conservation, while promoting ecological agriculture and sustainable resource management, reducing pressure on ecosystems, and strengthening enforcement of environmental regulations.

Narrowly coordinated areas such as Kondo Township need to promote ecological restoration projects, such as revegetation of degraded land and water purification. Optimize land use planning, balance ecological protection and economic development needs, and support community participation and local autonomy to improve the initiative and effectiveness of ecological protection.

Primary coordination areas such as Wanmao Town should promote eco-friendly agricultural practices, such as organic farming and crop rotation. Strengthen ecological education and training to enhance the ecological protection capacity of local residents, and establish ecological reserves to protect key ecosystems and biodiversity.

Intermediate coordination areas such as Narang Town should continue to promote ecological protection projects, such as forest protection and wetland restoration. Promote ecotourism and environmental education, raise public awareness of ecological values, and strengthen ecological infrastructure, such as ecological corridors and green transportation systems.

Well-coordinated areas such as Liulin Town should maintain and strengthen existing ecological protection measures to ensure the long-term stability of the ecosystem. Promote ecological innovation, such as the application of green technologies and sustainable materials, and establish ecological monitoring and evaluation systems to continuously track ecological conditions.

High-quality coordination areas such as Goye Town serve as models of ecological protection, demonstrating advanced ecological management and protection practices. Explore and implement eco-economic models, such as eco-agriculture and clean energy, and strengthen exchanges and cooperation with other regions to share successful experiences and technologies.

5.2. Ecological Function Zoning and Planning Management

The territorial spatial planning of Gansu Province aims to rationally divide various spatial functional areas, optimize spatial structure, improve the utilization efficiency of land and resources, protect the ecological environment, and promote sustainable economic and social development.

Combined with the previous studies in this study, the ecological function zoning and spatial pattern

Table 7 | Ecological corridor group information table

name	Number of towns crossed	Land use type	Roads (Main roads)	Rivers (main stream)
1. Ganga-sanko-treau Corridor Group	3	grassland	7	4
2. Muer - Dianga - Narang - Wangzang - Lazikou corridor Group	5	forest, grassland	0	1
3. Sangke - Kecai - Amu go Hu corridor Group	3	grassland	2	3
4. Gahai-eula-manzhima - Tsezhima Corridor Group	4	wetland, grassland	2	3

Table 8 | Ecological zoning strategies

Ecoregional types	Strategic perspectives	Specific strategies and measures
Ecological protection area	Protection and monitoring	Develop a visitor management plan, including visitor restrictions and education; Community involvement in conservation activities, such as ranger training; Establish ecological education centers to raise public awareness.
Ecological maintenance area	Conservation and sustainable use	Promote ecological agriculture to increase farmers' income and reduce the pressure on the natural environment; Establish a community co-management mechanism and encourage residents to participate in ecological protection.
Ecological development area	Control development and ecological compensation	Develop guidelines for environmentally friendly development and limit high-polluting projects; Provide preferential policies for industries with low ecological impact.
Ecological control area	Ecological restoration and risk management	Strengthen the enforcement of environmental laws and regulations and punish violations; Establish environmental monitoring stations to monitor environmental quality in real time.
Ecological enhancement area	Improved ecosystem services	Supporting local communities to develop ecotourism and environmental education programs; Encourage residents to participate in ecological restoration work and provide relevant skills training.
Ecological restoration area	Emergency repair and community involvement	Provide technical and financial support to help local communities participate in ecological restoration projects; Strengthen the late management and maintenance of ecological restoration areas.

planning of Gannan Prefecture were proposed, as shown in Figure 19. 1) Regarding ecological function zoning, Gannan Prefecture is divided into three zones: core area of ecological protection, improved area of ecological protection and important area of ecological protection. The core area of ecological protection is the key area of environmental protection in Gannan Prefecture, and the strictest protection measures are implemented to ensure the integrity of the ecosystem and biodiversity; The ecological protection and improvement zone aims to improve the quality of ecological environment and promote regional sustainable development through scientific management and rational utilization; The important areas of ecological protection focus on protecting key ecological functions and important natural resources, maintaining ecological balance, and ensuring regional ecological security. 2) Gannan Prefecture formed an overall pattern of "two cores - two axes - three regions". The two cores are the main ecological development cores and the secondary ecological development cores in the key areas of ecological protection and ecological construction. The two axes are the green ecological protection axis and the Yellow River charm corridor axis; The three areas are the important protection area, the key restoration area and the maintenance and improvement area.

Ecological function zoning and landscape spatial pattern planning, through scientific division and effective management of territorial space, ensure key ecological functions, improve environmental quality, and promote the coordinated development of economy, society and ecological environment, is an important means to achieve sustainable development and build a harmonious coexistence between man and nature. These plans not only improve the modernization of ecological and environmental governance, but also support balanced development among regions, safeguard ecological security, provide strong support for comprehensive decision-making, and play a core role in high-quality development, ecological urbanization and ecological civilization construction.

6. Conclusions

This study adopts the comprehensive source points of Gannan according to local conditions to construct the ecological security pattern, and well combines the theory of "mountains, rivers, forests, fields, lakes, grasses and sand" to identify ecological

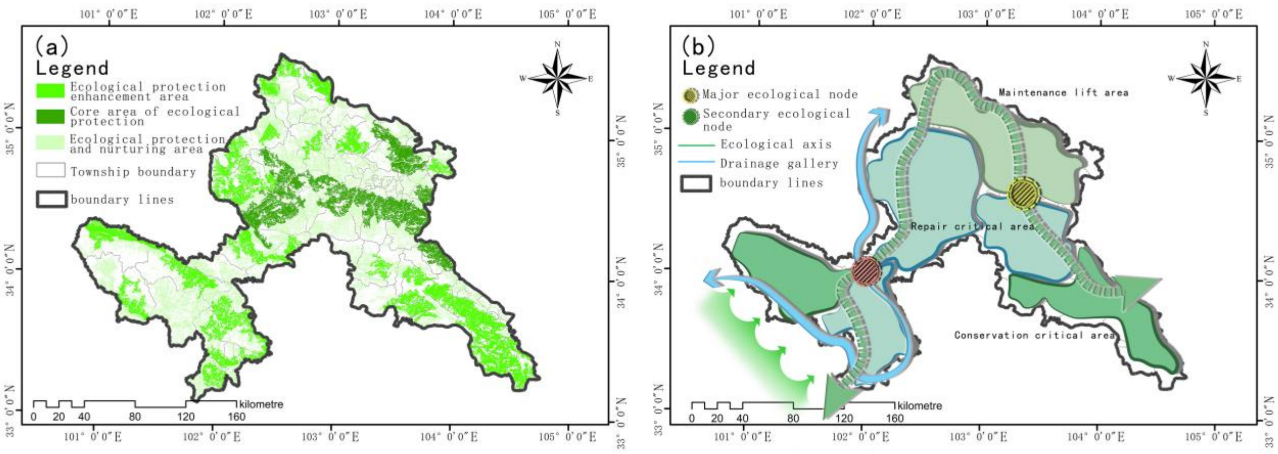

Figure 19 | (a) Ecological function zoning of Gannan Prefecture (b) Spatial landscape pattern planning of Gannan Prefecture

problems, and then combines these two approaches to propose ecological restoration strategies for Gannan. This method breaks the traditional "ecological security pattern", which is a single identification space for ecological restoration, and innovates the all-dimensional ecosystem of "ecological security pattern - ecological problem identification", which is more suitable for Gannan Prefecture and increases the richness of the whole article. This study also put forward a comprehensive "point-line-surface" restoration strategy suitable for Gannan Prefecture. Therefore, theoretically speaking, this study enriches the theoretical methods of ecological space restoration; It also provides a more detailed and comprehensive perspective for ecological problem identification. Realistically, the evaluation system and ecological spatial restoration strategy of this study are helpful for Gannan Prefecture to formulate a more scientific and reasonable regional ecological development plan, promote the coordination and unification of ecological environment protection and restoration.

In addition, it is important to acknowledge the limitations of the study. 1) Data source and quality. Studies may be limited by the quality and coverage of available data. If data collection is incomplete or biased, the results of network analysis may not be accurate enough. 2) Subjectivity of index selection. Although the multi-index evaluation system is adopted, the selection of indicators may still be subjective. Different indicators may identify areas of different ecological problems, and which indicators to choose and how to weigh their importance may require further validation and discussion. 3) Long-term effects and dynamic changes. Studies may not adequately consider long-term dynamic effects and the dynamics of ecological restoration over time in order to predict future ecological spatial restoration so that it can be prevented in advance.

Declaration of Competing Interest

The authors declare that we have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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A Framework for Promoting IoT- and Digital Twin-Enabled Intelligent Traffic Light Systems in China: an Empirical Study Based on a Malaysian Smart City Facilities Management Case

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KEYWORDS

Intelligent Traffic Light Systems,
Internet of Things,
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Smart Cities,
Sustainable Urban Development,
Traffic Optimization,
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Urban Infrastructure Management.

ABSTRACT

This study explores the potential for the implementation of an advanced Intelligent Traffic Light System (ITLS) in Chinese urban landscapes, integrating Internet of Things (IoT) and digital twin technologies for sustainable urban development. Using empirical data from the Malaysia Smart Traffic Light Management (MSTLM) program, we assessed the effectiveness of the system on multiple dimensions critical to sustainability. Statistical analysis of eight cities showed significant improvements in vehicle safety programs: average travel time was reduced by 37.7%, congestion index by 38.5%, fuel consumption by 27.3%, and CO_2 emissions by 18.4%. In addition, system reliability was significantly improved with 98.3% uptime and 280.5% increase in signal conditioning frequency. The study presents a comprehensive framework tailored to China's urban environment, emphasizing technical architectures, deployment strategies, and policy recommendations aligned with the SDGs. Our findings contribute to the debate on smart city infrastructure management, providing actionable insights for policymakers, urban planners, and stakeholders committed to resilient and sustainable urban growth providing an adaptable roadmap for large-scale deployment in rapidly urbanizing Chinese cities. Our findings bridge Malaysian empirical insights to China’s distinct infrastructure and governance structures.

1. Introduction

1.1. Background and Motivation

In recent decades, China's rapid urbanization has fostered unprecedented growth in metropolitan areas, leading to significant advances in infrastructure, economic development and technological innovation (Liu et al., 2024; Magazzino & Mele, 2021). However, this exponential urban expansion has triggered multifaceted challenges, especially in the area of urban traffic management. Growing car ownership exacerbates traffic congestion, leading to longer travel times, increased fuel consumption, higher CO2 emis-

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sions and significant economic losses (Leroutier & Quirion, 2023).

Traditional traffic management systems, which rely mainly on static signal timing and manual intervention, are increasingly unable to cope with the dynamic complexity of modern urban traffic. The management of transportation infrastructure facilities also presents obvious challenges. The proliferation of traffic monitoring equipment, signal control systems, and supporting infrastructure requires complex facilities management practices (Li et al., 2022). Traditional facility management practices often struggle to maintain optimal performance of these systems, resulting in increased maintenance costs and reduced system reliability. Modern traffic management facilities require intelligent monitoring systems and predictive maintenance protocols to ensure continuous operations and maximize the useful life of the infrastructure. However, existing literature seldom addresses how IoT and digital twin-based traffic systems, proven effective in smaller-scale pilot projects or developed regions, can be adapted to rapidly urbanizing environments with substantial infrastructural variations—a key gap this study aims to fill.

At the same time, the pressing global need for sustainability shows that innovative solutions must be employed to mitigate environmental impacts while improving the livability of cities (Bibri & Krogstie, 2020; Wu, 2023). The integration of cutting-edge technologies such as the Internet of Things (IoT) and digital twins offers transformative opportunities for positive change in transportation management. The IoT can facilitate real-time data collection and communication between interconnected devices, allowing for adaptive and intelligent control mechanisms (Khan et al., 2023). On the other hand, digital twin technologies can provide a virtual copy of the physical transportation system, granting the possibility of comprehensive simulation and predictive analysis (Qian et al., 2022). The convergence of these technologies in Intelligent Traffic Light Systems (ITLS) is not only expected to optimize traffic flow and reduce congestion, but also contribute significantly to environmental sustainability and economic efficiency.

The Malaysian Smart Traffic Light Management (MSTLM) project is a relevant empirical case study that demonstrates the tangible benefits of ITLS implementation. By analyzing data from eight major cities in Malaysia, this study attempts to extrapolate insights and develop a robust framework tailored for the Chinese urban environment. The overarching motivation is to leverage technological advances to promote sustainable urban development, improve the efficiency of traffic management, and align with the global Sustainable Development Goals (SDGs).

1.2. Research Objectives

This study is driven by a multifaceted set of objectives aimed at comprehensively evaluating and facilitating the adoption of ITLS in Chinese cities:

- **Evaluate the Effectiveness of IoT-Enabled Traffic Light Systems**: Through empirical analysis of operational data from the MSTLM project, assess the impact of ITLS on key performance indicators such as travel time efficiency, congestion indices, fuel consumption, and CO_2 emissions.
- **Develop an Implementation Framework for Chinese Urban Environments**: Formulate a comprehensive framework that addresses the unique technical, economic, and environmental contexts of Chinese cities, ensuring seamless integration and scalability of ITLS.
- **Assess Technical, Economic, and Environmental Impacts**: Conduct a holistic evaluation of ITLS implementation, encompassing technical architecture, cost-benefit analyses, and environmental sustainability metrics.
- **Propose Policy Recommendations for Large-Scale Deployment**: Formulate actionable policy guidelines that facilitate the widespread adoption of ITLS, fostering public-private partnerships, ensuring regulatory compliance, and promoting sustainable urban governance.

This leads to our core research question: Can IoT- and digital twin-enabled traffic light systems, validated in the Malaysian MSTLM project, produce significant sustainability gains in the complex urban environments of China?

1.3. Significance of the Study

As one of the most rapidly urbanizing countries in the world, China is at a critical juncture where the integration of MSTLM can have far-reaching impacts in terms of economic benefits, environmental sustainability and improved quality of urban life (Hui et al., 2023). By carefully analyzing the results of the MSTLM project, this study provides valuable empirical evidence to support the effectiveness of ITLS, thereby informing policy makers, urban planners, and stakeholders of the practical advantages and strategic considerations necessary for successful ITLS implementation.

In addition, a tailored implementation framework addresses the nuanced challenges inherent in large-scale urban deployments, such as infrastructure diversity, governance structures, and socioeconomic disparities. This study not only illustrates the technical and environmental advantages of ITLS, but also emphasizes the need to promote collaborative governance models and incentivize public-private partnerships to drive sustainable urban transformation. It is in line with the global sustainable development agenda to promote resilient and inclusive urban communities through the judicious application of advanced (Wu, 2024).

2. Literature Review

2.1. Evolution and Components of ITLS

ITLS represent a transformative evolution from traditional static traffic signal control to a dynamic, data-driven management framework. ITLS utilizes real-time data collection, processing, and adaptive control mechanisms to optimize traffic flow, reduce congestion, and enhance overall urban mobility (Elassy et al., 2024). ITLS deployments have been associated with significant improvements in travel time efficiency, fuel consumption, and emission reductions (Toulni et al., 2023).

The evolution of ITLS can be traced from basic traffic signals equipped with sensors to complex systems integrating advanced analytics and machine learning algorithms. The core components of an ITLS include traffic sensors (e.g., cameras, inductive loops), traffic control units (TCUs), IoT gateways, and communication networks (Rai et al., 2023). The integration of digital twin technology further enhances the ITLS by providing a virtual copy of the physical transportation system, facilitating simulation, predictive maintenance, and scenario analysis (Adel & HS Alani, 2024).

Empirical studies have consistently demonstrated the effectiveness of ITLS in alleviating traffic congestion, reducing travel time, and reducing greenhouse gas emissions (Kuang et al., 2019; J. A. Molina et al., 2020). For example, deployments in cities such as Singapore and Barcelona have significantly reduced peak hour travel times and fuel consumption (L. T. Molina et al., 2019; Savall-Mañó et al., 2024). However, challenges remain, including high initial deployment costs, interoperability issues with legacy systems, and concerns related to data privacy and security (Albouq et al., 2022).

2.2. IoT in Urban Traffic Management

IoT constitutes a network of interconnected devices capable of collecting, exchanging and analyzing data autonomously. In the context of urban traffic management, IoT facilitates real-time data acquisition from various sensors for dynamic traffic signal adjustments and informed decision making (Almutairi et al., 2024).

The IoT architecture for traffic management typically consists of a sensor layer, a communication layer, and an application layer (Rai et al., 2023). Protocols such as MQTT, CoAP, and Ethernet play a crucial role in ensuring efficient data transfer and interoperability between devices (Seoane et al., 2021). The emergence of 5G technology further enhances the capabilities of IoT for traffic management by providing high-speed, low-latency communications essential for real-time applications (Sefati & Halunga, 2023).

Many case studies highlight the successful integration of IoT in traffic management systems. In Türkiye, smart cities intelligent transportation systems project demonstrates the application of IoT in optimizing traffic flow and reducing congestion through real-time data analysis and adaptive control mechanisms (Gunes et al., 2021). Similarly, initiatives in European cities have achieved significant improvements in transportation efficiency and environmental sustainability through IoT-enabled ITLS deployments (Elassy et al., 2024).

Recent studies (Alfandi et al., 2021) stress the importance of data security and privacy in IoT-centric traffic systems. Particularly in large-scale Chinese cities, ensuring secure data streams and compliance with data governance policies is a critical success factor for widespread ITLS adoption.

2.3. Digital Twin Technology in Traffic Management

Digital twin technology involves creating virtual counterparts of physical systems for comprehensive monitoring, simulation and optimization (Botín-Sanabria et al., 2022; Javaid et al., 2023). In traffic management, digital twins help in visualization of traffic dynamics, predictive analytics and scenario testing to enhance the decision-making process (Ersan et

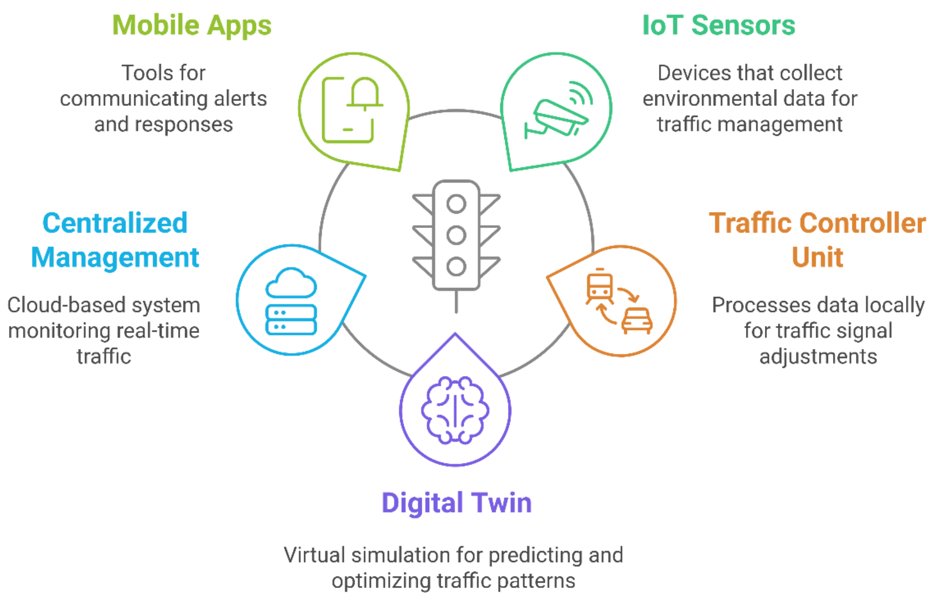

Figure 1 I Conceptual Framework

al., 2024). Digital twins typically involve the integration of real-time data streams with simulation models to create dynamic virtual environments that offer several advantages (Kušić et al., 2023), including enhanced predictive maintenance, improved traffic forecasting, and the ability to simulate the impact of infrastructure changes (Werbińska-Wojciechowska et al., 2024).

2.4. Sustainable Urban Development and Smart Cities

Sustainable urban development seeks to balance economic growth, environmental stewardship and social equity in urban settings (Kajiita & Kang'ethe, 2024). Smart cities, characterized by the integration of advanced technologies and data-driven governance, play a crucial role in achieving the sustainable development goals by improving the efficiency of urban services and infrastructure (Bibri, 2021). Intelligent traffic signal systems contribute to sustainable urban development by optimizing traffic flow, reducing vehicle emissions and improving the quality of urban life (Musa et al., 2023). By minimizing congestion and improving travel time efficiency, ITLS reduces fuel consumption and greenhouse gas emissions, thereby mitigating the environmental impact of urban transport (Elassy et al., 2024; Kuang et al., 2019). The effectiveness of ITLS is amplified when combined with other urban systems such as public transportation, emergency services and urban planning frameworks (Glazener et al., 2021).

2.5. Gaps in the Literature

Figure 1 conceptualizes the interdependencies between ITLS, IoT, and digital twin technologies, illustrating how real-time sensor inputs and predictive simulations converge to improve traffic management outcomes. This framework guides our empirical inquiries and informs the subsequent methodological design.

While substantial progress has been made in understanding the benefits and challenges of ITLS, some gaps remain. Notably, there is limited research on the contextual adaptation of ITLS to different urban environments, especially in rapidly urbanizing environments like China. Addressing these gaps is critical to developing comprehensive implementation frameworks that take into account the unique infrastructural, socioeconomic, and governance landscapes of different urban environments.

3. Methodology

3.1. Research Design

This study employs a quantitative research design, focusing exclusively on the analysis of empirical data from the MSTLM project. The objective is to evaluate the effectiveness of ITLS in improving urban traffic

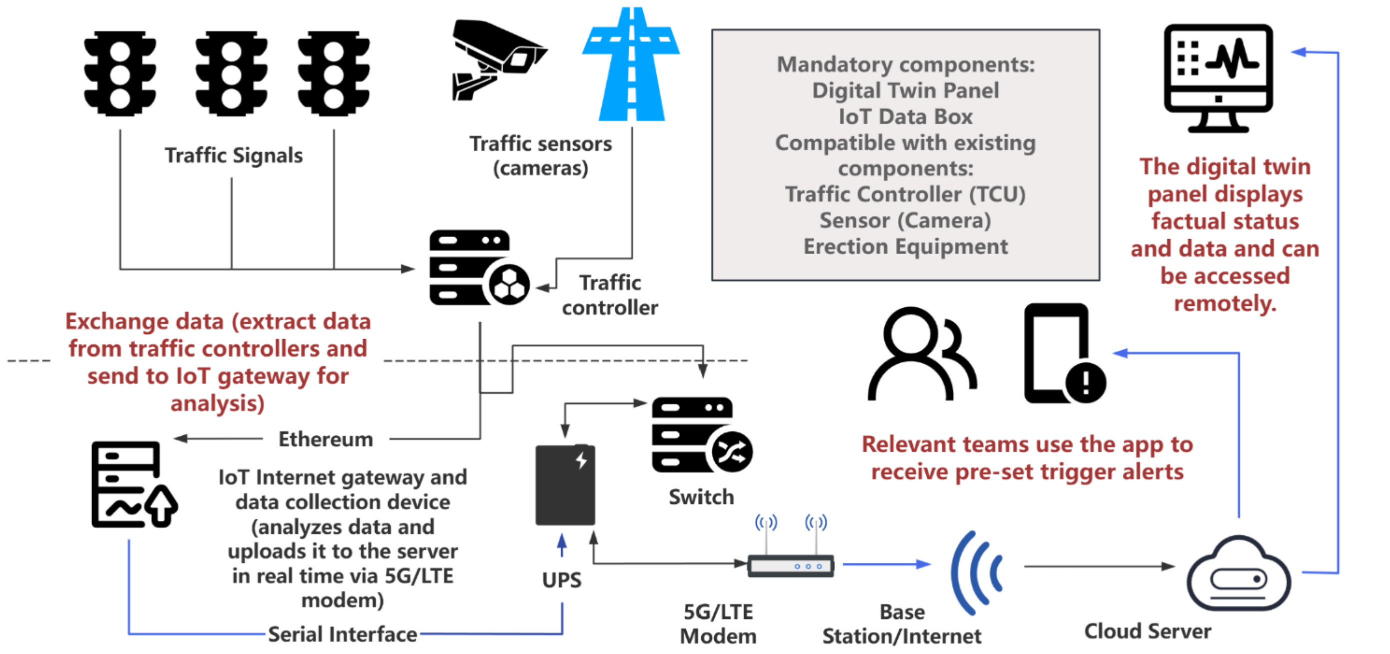

Figure 2 I MSTLM Technical Architecture Diagram

management and contributing to sustainable urban development. By leveraging statistical methods, the research aims to quantify the impact of ITLS across key performance indicators (KPIs) such as travel time efficiency, congestion index, fuel consumption, and CO_2 emissions.

3.2. Data Collection

Data for this study is sourced solely from the MSTLM project implemented in eight Malaysian cities. The data encompasses both pre-implementation and post-implementation metrics, providing a comprehensive basis for comparative analysis.The MSTLM dataset spans 12 months (from Feb 23 to Feb 24), capturing peak and off-peak traffic data in 30-minute intervals. Each city's dataset was consolidated into daily and weekly averages to align with the availability of maintenance logs and emission measurements.

The eight cities were selected based on (1) having established traffic sensor infrastructure, (2) government collaboration, and (3) diverse roadway characteristics (urban cores, suburban zones, etc.). This purposive selection provides a broad spectrum of traffic conditions while ensuring data comparability.

3.2.1. Operational Metrics:

- **Travel Time Efficiency**: Peak hour travel time measurements before and after ITLS implementation.
- **Congestion Index**: Real-time traffic flow data before and after ITLS implementation.
- **Fuel Consumption**: Daily fuel consumption rates before and after ITLS implementation.
- CO_2 Emissions: Daily CO_2 emission levels before and after ITLS implementation.

3.2.2. System Performance Metrics:

- System Uptime: Percentage of time the ITLS was operational.
- Daily Signal Adjustments: Number of daily adjustments made to traffic signals before and after ITLS implementation.

3.3. Data Analysis

The data collected was analyzed using robust statistical techniques to assess the impact of the ITLS on urban traffic management and sustainability indicators. The following methodology was used:

3.3.1. Descriptive Statistics

Descriptive statistics provide a basic understanding of the data by summarizing the central tendency, dispersion, and overall distribution of KPIs before and after the implementation of the ITLS.

- **Mean and Standard Deviation**: Calculate the average values and variability for each KPI across the eight cities.
- **Percentage Reduction/Improvement**: Determine the percentage change in each KPI post-implementation relative to pre-implementation values.

3.3.2. Paired t-Tests

A paired t-test was conducted to compare the means of the KPIs before and after ITLS implementation. This statistical test assesses whether the differences observed in the indicators are statistically significant. All t-tests were conducted in SPSS , and p-values are reported to three decimal places to ensure transparency.

3.3.2.1. Hypothesis Testing:

- **Null Hypothesis (H_1)**: There is no significant difference in the KPI before and after ITLS implementation.
- **Alternative Hypothesis (H_1)**: There is a significant difference in the KPI before and after ITLS implementation.

3.3.2.2. Significance Level:

A p-value of less than 0.05 is considered statistically significant.

3.4. Limitations

While the study provides valuable insights into the impact of ITLS, certain limitations must be acknowledged:

Table 1 I ITLS System Architecture Overview

Layer	Components	Description
Field Layer	• Traffic Signal Units • Traffic Sensors (Cameras) • Traffic Control Units (TCUs)	Core execution units managing vehicle flow, monitoring traffic conditions, and performing initial data processing.
Communication Layer	• Ethernet Protocol • Serial Interfaces • 5G/LTE Modems • Base Stations/Internet Connectivity	Facilitates data exchange, robust transmission, high-speed communication, and wide-area network support.
Processing Layer	• IoT Gateways and Data Acquisition Devices • Cloud Servers • Uninterruptible Power Supply (UPS) Systems • Switches	Handles real-time data analysis, extensive processing, power stability, and internal network communications.
Application Layer	• Digital Twin Panels • Mobile Applications • Remote Access Interfaces	Provides real-time visualization, remote monitoring, and centralized management capabilities.

Table 2 I ITLS Data Flow Processes

Process	Steps
Data Collection	1. Traffic signals and sensors capture real-time traffic data. 2. Traffic controllers process initial data locally. 3. IoT gateways aggregate and transmit data to cloud servers.
Data Processing	1. Real-time analysis by IoT gateways. 2. Data transmitted via 5G networks to cloud servers. 3. Cloud servers perform advanced analytics and store data. 4. Insights visualized on digital twin platforms.
Control Process	1. Decision-making on digital twin panels. 2. Instructions sent to cloud servers. 3. Cloud servers relay instructions to IoT gateways. 4. IoT gateways direct traffic controllers to execute signal adjustments.

- **Geographical Specificity**: The empirical data is exclusively from Malaysian cities, which may have different infrastructural and socio-economic contexts compared to Chinese cities.
- **Data Granularity**: Limited access to more granular data (e.g., minute-by-minute traffic flow) may constrain the depth of analysis.
- **Technological Variability**: Differences in ITLS technologies and implementation strategies across cities may introduce variability in the outcomes.

4. Results and Analysis

4.1. System Design and Implementation

ITLS implemented in the MSTLM project is based on a complex technological architecture integrating the IoT and digital twin technologies. Figure 2 in this section depicts the comprehensive system design, highlighting each architectural layer and its constituent components through structured Table 1 and Table 2 . In addition, it describes the system integration and data flow processes.

4.2. Empirical Data Analysis

The empirical analysis utilized quantitative data from the MSTLM program, focusing on eight major cities. The analysis assessed the impact of ITLS implementation on KPIs that are critical to sustainable urban development, including travel time efficiency, congestion index, fuel consumption, carbon dioxide emissions, system reliability, and frequency of signal adjustments.

4.2.1. Travel Time Efficiency

According to Table 3 ITLS implementation significantly reduced peak hour travel times in eight cities. Shah Alam City experienced the greatest improvement with a 45.0% reduction in travel time. On average, travel time decreased from 32.8 minutes to 20.4 minutes, a 37.7% reduction. A paired t-test confirmed the statistical significance of this reduction ($p= 0.003$).

(H_1: Average Peak Hour Travel Time Reduction: 37.7%)

4.2.2. Congestion Reduction

The congestion index, a key measure of traffic density and traffic efficiency, improved by an average of 38.5% after the implementation of ITLS as shown in Table 4. The pre-implementation average congestion index was 73.6%, which dropped to 45.3% after ITLS deployment. The city of Shah Alam City again showed the most significant decrease at 45.0%, while the other cities also showed significant improvements. A paired t-test confirms the statistical significance of these findings ($p = 0.002$).

(H_1: Average Congestion Index Improvement: 38.5%)

4.2.3. Fuel Consumption

As shown in Table 5, the deployment of the ITLS resulted in an average reduction of 27.3% in daily fuel

Table 3 | Travel Time Efficiency Before and After ITLS Implementation

City	Number of intersections	Percentage	Before implementation (minutes)	After implementation (minutes)	Reduction rate (%)
Kuala Lumpur	550	30.6%	45	28.5	36.7
Penang	320	17.8%	35	22.5	35.7
Johor Bahru	280	15.6%	38	24.5	35.5
Shah Alam	180	10.0%	32	19.7	38.5
Putrajaya	150	8.3%	25	16.0	36.0
Cyberjaya	120	6.7%	32	17.6	45.0
Kota Kinabalu	110	6.1%	28	17.5	37.5
Kuching	90	5.0%	27	17.2	36.3
Average	1,800	100%	32.8	20.4	37.7

consumption, which equates to a savings of approximately 1,390 liters of fuel per day per city. Shah Alam City reported the largest reduction of 45.0%, while the other cities reported reductions ranging from 23.5% to 25.5%. A paired t-test verified the statistical significance of these reductions ($p = 0.004$).

(H_1: Average Congestion Index Improvement: 38.5%)

4.2.4. CO_2 Emissions

The implementation of ITLS resulted in an average reduction of 18.4% in daily CO_2 emissions in the cities studied. Table 6 shows that the reductions ranged from 15.4% to 35.0%. The paired t-test confirmed the statistical significance of these reductions ($p = 0.008$).

(H_1: CO_2 Emissions Decrease: 18.4%)

4.2.5. System Reliability

ITLS has demonstrated excellent reliability, maintaining an average uptime of 98.3%. Monthly downtime has been reduced to an average of 12.4 hours, ensuring continued efficient traffic management. This high level of system reliability demonstrates the effectiveness of the robust architectural design and the redundancy and fail-safe mechanisms implemented.

4.2.6. Daily Signal Adjustments

With the implementation of ITLS, the frequency of daily signal adjustments increased dramatically from an average of 49.9 adjustments per day to 188.8 ad-

Table 4 | Congestion Index Before and After ITLS Implementation

City	Before implementation (minutes)	After implementation (minutes)	Reduction rate (%)
Kuala Lumpur	85.0	54.4	36.0
Penang	78.0	48.4	38.0
Johor Bahru	80.0	49.6	38.0
Shah Alam	72.0	44.3	38.5
Putrajaya	65.0	40.3	38.0
Cyberjaya	75.0	41.3	45.0
Kota Kinabalu	68.0	42.2	37.9
Kuching	66.0	41.6	37.0
Average	73.6	45.3	38.5

Table 5 | Fuel Consumption Before and After ITLS Implementation

City	Before implementation (liters/day)	After implementation (liters/day)	Reduction rate (%)
Kuala Lumpur	8,500	6,290	26.0
Penang	5,500	4,180	24.0
Johor Bahru	6,000	4,500	25.0
Shah Alam	4,800	3,576	25.5
Putrajaya	3,500	2,660	24.0
Cyberjaya	5,000	2,750	45.0
Kota Kinabalu	3,800	2,890	24.0
Kuching	3,700	2,830	23.5
Average	5,100	3,710	27.3

justments per day. This 280.5% increase reflects the system's increased ability to adapt to real-time traffic conditions, thereby optimizing traffic flow and reducing congestion.

4.3. Statistical Significance

Paired t-tests across all KPIs showed a statistically significant improvement after implementation of ITLS, with p-values well below the conventional threshold of 0.05. These results confirm that the observed reductions in travel time, congestion, fuel consumption, and CO_2 emissions, as well as improvements in system reliability and frequency of signal conditioning, are not due to random variations, but rather are important outcomes of ITLS implementation.

5. Discussion

5.1. Key Finding

The results presented in Chapter 4 highlight the transformative potential of ITLS that integrate IoT and digital twin technologies. Empirical data from eight major cities in Malaysia show statistically significant improvements in travel time efficiency, congestion reduction, fuel consumption, CO_2 emissions, system reliability, and frequency of signal adjustments.

5.1.1. Technical and Operational Implications

Real-time Adaptation and Frequent Signal Adjustments: The significant increase in daily signal adjustments highlights the need for traffic management systems that can instantly respond to fluctuating road

Table 6 I CO2 Emissions Before and After ITLS Implementation

City	Before implementation (tons/day)	After Implementation (tons/day)	Reduction rate (%)
Kuala Lumpur	20.4	17.1	16.2
Penang	13.2	11.1	15.9
Johor Bahru	14.4	12.0	16.7
Shah Alam	11.5	9.6	16.5
Putrajaya	8.4	7.1	15.5
Cyberjaya	16.0	10.4	35.0
Kota Kinabalu	9.1	7.7	15.4
Kuching	8.9	7.5	15.7
Average	12.7	10.3	18.4

Table 7 I System Reliability Before and After ITLS Implementation

City	Running time (%)	Monthly downtime (hours)
Kuala Lumpur	97.8	16.2
Penang	98.2	13.3
Johor Bahru	98.0	14.6
Shah Alam	98.4	11.7
Putrajaya	98.6	10.2
Cyberjaya	99.2	5.8
Kota Kinabalu	97.9	15.3
Kuching	98.3	12.4
Average	98.3	12.4

Table 8 | Daily Signal Adjustments Before and After ITLS Implementation

City	Pre-implementation	Post-implementation	Increase (%)
Kuala Lumpur	80	295	268.8
Penang	55	205	272.7
Johor Bahru	60	230	283.3
Shah Alam	45	175	288.9
Putrajaya	35	140	300.0
Cyberjaya	50	180	260.0
Kota Kinabalu	38	145	281.6
Kuching	36	140	288.9
Average	49.9	188.8	280.5

conditions. IoT-driven controllers and digital twin models play a crucial role in facilitating these dynamic adaptations (Hashem et al., 2024).

Digital twin integration: integrating IoT gateways for data collection and cloud-based digital twin platforms for traffic simulation significantly improves decision-making (Irfan et al., 2024). The predictive power of the digital twin environment enables city managers to anticipate and mitigate congestion before it intensifies.

Scalability and Resiliency: The layered architectural design (including field, communications, processing, and application layers) is scalable, enabling incremental system expansion. In addition, power backup (UPS) and redundant communication channels minimize downtime, which is critical in high-density urban environments.

Environmental Sustainability: Significant reductions in fuel consumption and CO_2 emissions are consistent with broader green development goals (Zakari et al., 2022). These findings suggest that ITLS, when integrated into a city's sustainability agenda, can make a tangible contribution toward mitigating environmental impacts.

5.1.2. Economic Considerations

Cost Benefit Advantage: While the initial capital investment (for IoT sensors, communications upgrades, and cloud services) can be large, the reduction in congestion-related costs (lost productivity, excessive fuel use, and vehicle maintenance) supports a favorable long-term return on investment (ROI).

Scalable Deployment: Incremental deployment (e.g., focusing on high-priority intersections first) can help municipalities manage financial expenditures while reaping immediate benefits. Successful pilot projects can attract additional funding or incentives for broader system rollouts.

5.1.3. Policy and Governance Factors

Standardization and Interoperability: Unified data exchange protocols and sensor specifications simplify integration and reduce the complexity of integrating various traffic control units and cameras (Naveed et al., 2022).

Public-private partnerships: Partnering with technology companies and system integrators can offset capital costs and accelerate knowledge transfer. Clear procurement guidelines and performance-based contracts help align incentives.

Capacity Building: Facilities managers and traffic engineers need ongoing training in IoT data management, predictive analytics, and digital twin operations. Investment in skill development is critical to sustain long-term system performance.

Data Governance and Compliance: Harmonizing ITLS data streams with local cybersecurity laws (e.g., China's Data Security Law) and ensuring locally hosted servers for sensitive traffic footage can be crucial to maintaining public trust and avoiding legal complications.

5.2. Implementation Framework for Chinese Citiess

Based on the quantitative evidence and operational insights gained from the MSTLM project, we attempt to articulate a strategic roadmap that can be used to deploy ITLS in Chinese urban environments. The framework recognizes the diversity of infrastructures, the complexity of systems, and the high population densities in many of China's urban areas. By integrating technical, operational, and policy-oriented strategies, the proposed implementation framework aims to simplify the deployment of ITLS for sustainable and smart urban traffic management.

In China's context, high population densities and complex governance structures necessitate greater emphasis on inter-agency coordination. Our pilot-based approach could be initially tested in Tier 1 cities (e.g., Shanghai or Guangzhou) before scaling to mid-sized cities.

5.2.1. Phased Deployment Strategy

A three-phase approach ensures that ITLS implementation is systematic, adaptive, and scalable. Each phase addresses key considerations in infrastructure, technology, stakeholder engagement, and policy alignment.

5.2.1.1. Phase 1: Infrastructure Assessment and Planning

1) Network Evaluation

- Bandwidth and Coverage: Conduct city-wide surveys to evaluate existing cellular networks (e.g., 4G/LTE, 5G) and fiber backbones. Identify zones with inadequate coverage and plan expansions or upgrades.
- Latency Requirements: Set benchmarks for maximum permissible latency (e.g., 100 ms) to support real-time signal adjustments and IoT data streaming.

2) Legacy System Compatibility

- Controller and Sensor Audit: Catalog existing traffic controllers, sensors, and traffic lights. Determine which can be integrated via compatibility modules (e.g., serial-to-Ethernet converters) and which require replacement.
- Protocol Alignment: Adopt standardized communication protocols (e.g., MQTT, CoAP, Ethernet) to minimize integration conflicts and ensure consistent data formatting.

3) Stakeholder Engagement

- Inter-departmental Collaboration: Form a steering committee with representatives from transportation, IT, public security, and urban planning agencies to unify decision-making.
- Public-Private Partnerships (PPPs): Explore collaborations with telecommunications companies and technology vendors, leveraging private-sector expertise and shared investment models.

5.2.1.2. Phase 2: Pilot Implementation

1) High-Priority Intersections

- Site Selection Criteria: Focus on intersections with chronic congestion, high accident rates, or strategic importance (e.g., CBDs, access points to highways).
- Pilot Scale: Start with a manageable number of intersections (e.g., 10–20) to validate the technical architecture and fine-tune system parameters before city-wide rollout.

2) Core ITLS Components

- IoT Gateways and Cloud Services: Install IoT gateways at selected intersections and configure cloud servers to process incoming data in real time.
- Digital Twin Panels: Develop interactive dashboards displaying real-time traffic flows, congestion indices, and predictive scenarios for each pilot site.
- Edge Processing: For latency-critical tasks, consider deploying edge computing nodes near intersections, reducing the round-trip time to cloud servers.

3) Performance Monitoring and Adjustment

- Pilot Selection: We recommend a 6-month pilot cycle to capture seasonal variations in traffic patterns.
- KPI Tracking: Continuously monitor travel times, congestion indices, and fuel consumption metrics via live dashboards.
- Iterative Fine-Tuning: Adjust signal timings and sensor calibration (e.g., camera angles, detection zones) based on real-time data and operator feedback.
- Public Feedback Loop: Integrate user feedback—particularly from drivers, commuters, and local businesses—to refine pilot implementation and bolster community support.

5.2.1.3. Phase 3: Full-Scale Rollout

1) City-Wide Integration

- Incremental Expansion: Deploy ITLS across all major intersections, prioritizing those with high traffic volume and strategic significance.
- Cluster-Based Rollout: Roll out in clusters (e.g., districts or zones) to manage complexity and consolidate data analytics for each area.

2) Adaptive Optimization

- Seasonal and Event-Based Adjustments: Use time series analysis to preemptively modify signal timings during holidays, special events, or seasonal peaks (e.g., monsoon seasons).
- Machine Learning Algorithms: Incorporate AI-driven pattern recognition to optimize signal timing, particularly for unpredictable traffic surges (e.g., accidents, sporting events).

3) Multi-Modal Integration

- Public Transit Synchronization: Align ITLS adjustments with bus rapid transit (BRT) or metro schedules, prioritizing public transport corridors during peak hours.
- Non-Motorized Modes: Implement pedestrian-friendly signal phases and consider bicycle lane integration, reducing vehicular dependency and supporting green mobility.

5.2.2. Technical Infrastructure Requirements

Reliable communication networks, scalable computing solutions, and robust security measures form the backbone of a well-functioning ITLS. Meeting these requirements ensures that frequent signal adjustments, real-time analytics, and digital twin simulations can be performed without technical bottlenecks.

5G/LTE Capacity Planning: Forecast data usage based on sensor density and update rates. Each intersection may generate multiple streams of video/telemetry data.

Secure Access Control: Implement multi-factor authentication (MFA) for control systems, ensuring only authorized personnel can modify signal parameters.

Facilities Maintenance Protocols: Establish regular cleaning, alignment checks, and firmware updates to minimize sensor drift or degradation.

IoT Protocol Compatibility: Promote uniform adoption of open standards (MQTT, CoAP) or widely used industrial protocols (e.g., Modbus over TCP) for ease of integration.

5.2.3. Risk Management

Comprehensive risk management addresses technical, operational, and stakeholder-related uncertainties. Proactive mitigation enhances system reliability, sustainability, and public acceptance.

Bridging Modules: Bridge Module: Prepare adapters/converters to connect older traffic controllers or sensors to modern IoT gateways. Greater compatibility with deployed devices, reduced costs and improved overall stability.

Scheduled Downtime: Enables facilities management teams to plan system updates and maintenance periods during off-peak hours to minimize disruptions.

Skill Shortages: Organize workshops and certification programs for facilities management teams focusing on system configuration, predictive analytics, and digital twin usage. Also develop a centralized repository of standard operating procedures (SOPs), lessons learned, and best practices that can be accessed by all departments.

5.3. Conclusion

The above framework provides a structured blueprint for Chinese cities seeking to deploy ITLS at scale. By dividing deployment into carefully managed phases, supported by a strong technical infrastructure and stakeholder collaboration, relevant government authorities can mitigate risk and ensure continuous performance improvement (Nübel et al., 2021). In addition, aligning the ITLS with broader city development strategies, particularly around environmental sustainability and economic viability, can enhance its effective long-term sustainability.

6. Conclusions and Recommendations

6.1. Summary of Research

Drawing empirical evidence from the MSTLM project, this thesis provides a rigorous exploration of an IoT-driven, digital twin-enhanced ITLS. By juxtaposing the theoretical foundations of adaptive traffic control with real-world data collected from eight major cities in Malaysia, this work confirms the transformative power of ITLS. From the outset, this research was driven by one overarching question: Can an IoT-centric layered architecture solution effectively reduce urban congestion and produce sustainable mobility outcomes?

The investigation addresses this issue by profiling multifaceted performance metrics, including travel time, congestion index, fuel consumption, CO_2 emissions, and overall system resilience. Chapters 1 through 5 provide the conceptual background, methodological framework, and detailed empirical findings, culminating in strategic recommendations for large-scale adoption in Chinese cities. This chapter summarizes the study, synthesizes the accumulated insights, describes the broader implications, and provides a roadmap for continued engagement in the scholarship and practice of ITLS.

6.2. Key Results

6.2.1. Efficacy Across Core Metrics

Empirical data demonstrates the significant enhancement of traffic flow and environmental indices. Travel time efficiency soared by an average of 37.7%, while the congestion index dropped by 38.5%, highlighting the real-time adaptability of ITLS. Meanwhile, daily fuel consumption dropped by 27.3% and CO_2 emissions by 18.4%. Taken together, these results underscore the system's ability to contribute to tangible sustainability gains in urban mobility.

6.2.2. Robust Technical Underpinnings

Empirical evidence demonstrates that a layered ITLS architecture, including field, communication, processing, and application layers, helps ensure system robustness. Supported by 5G/LTE networks, real-time data streaming facilitates instantaneous signal tuning, while digital twin environments optimize prediction (Maiwada et al., 2024). This synergy of edge processing and cloud analytics provides the foundation for near-seamless traffic orchestration, resulting in 98.3% operational uptime and minimal downtime.

6.2.3. Economic and Environmental Justifications

While the initial capitalization of IoT integrations and infrastructure upgrades may seem daunting, MSTLM data confirms the long-term return on investment (ROI). Reduced vehicle idle time, reduced accident risk, and streamlined traffic flow combine to lower operating costs and greenhouse gas emissions. As a result, cities ready to implement ITLS will realize economic relief and ecological dividends over time, creating a virtuous cycle.

6.2.4. Policy-Driven Scalability

Aligning system deployments with an incremental strategy framework (especially in the areas of standardization, interoperability, and public-private collaboration) becomes critical. Harmonized protocols and centralized data governance accelerate citywide deployments, ensuring that Advanced Traffic Management is no longer an isolated pilot, but evolves into a sustainable and scalable growing smart city effort.

6.3. Contributions to Knowledge

6.3.1. Empirical Validation in Emerging Urban Contexts

While adaptive signal control is not novel, this dissertation enriches the literature by applying IoT and digital twin insights to a rapidly urbanizing region. The empirical rigor across multiple cities goes beyond the single case studies usually limited to advanced metropolitan areas, thus broadening the generalizability of ITLS efficacy.

6.3.2. Fusion of Technological and Environmental Outcomes

By focusing on simultaneous improvements in system reliability and environmental metrics, the study highlights an often-overlooked synergy: high-frequency signal tuning can both smooth traffic and achieve carbon containment. This dual emphasis amplifies the argument for integrated urban planning that encompasses IoT-based solutions within broader sustainability policies.

6.3.3. Blueprint for Collaborative Governance

Beyond the purely technical findings, the study reveals that governance - particularly cross-sectoral committees, data sovereignty issues, and PPP mechanisms - provides a more nuanced view of how ITLS can thrive in complex urban ecosystems. The interplay of shared responsibility, standardized protocols, and capacity building underscores the socio-technical nature of truly smart traffic management.

6.4. Future Research Directions

6.4.1. Synergistic Integration With Autonomous Vehicles

As autonomous driving technologies mature, it is critical to study the interactions between ITLS and connected fleets. Machine-to-machine negotiation at intersections, dynamic re-routing, and advanced collision avoidance protocols require cohesive research that connects traffic engineering and AI (Bittencourt et al., 2024).

6.4.2. Advanced Machine Learning Algorithms

Future implementations may deploy reinforcement learning or deep neural networks to continuously optimize intersection control with minimal human intervention (Elallid et al., 2022). Such algorithms could leverage real-time "experience" to outperform static traffic signal planning, especially in the presence of unpredictable traffic surges.

6.4.3. Potential of Different Types of Cities

We encourage multi-city replication studies in geographically diverse Chinese provinces to validate the universal applicability of these findings and to capture potential regional constraints such as rural vs. urban traffic patterns and industrial vs. service-oriented city layouts.

6.5. Concluding Remarks

In an era of burgeoning urban populations and demands outpacing outdated traffic management methods, smart traffic light systems powered by IoT data streams and digital twin predictions represent beacons of practical innovation and open up possibilities for further visions of facilities management.

While MSTLM experience exemplifies these benefits, the proposed implementation framework and policy recommendations aim to inspire similar successes in China's urban landscape. Each metropolis has its own nuanced challenges and prospects, and these guidelines can be adapted to local realities, opening the way for a more fluid, low-carbon, and citizen-centered transportation ecosystem. Ultimately, the synergy of forward-thinking governance, big data algorithms, and AI may well make the notion of "traffic chaos" a footnote in history, replaced by a dynamic, sustainable, and intelligent urban tapestry that harmoniously blends technology and humanity.

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