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Urban Expansion, Climate Vulnerability, and Transportation Resilience: Insights for Sustainable Development

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Abstract. Climate change poses a significant threat to transportation infrastructure, particularly in rapidly urbanizing regions like Bumi Serpong Damai (BSD) City, Indonesia, which faces increased risks of flooding and the urban heat island (UHI) phenomenon. However, limited research has assessed the combined impacts of climate and land use changes on infrastructure resilience. This study addresses this gap by integrating remote sensing analysis, climatological data, field observations, and stakeholder interviews to identify key vulnerabilities. The results highlight that low-lying and high-impermeability areas, such as the BSD highway and Central Business District (CBD), are highly susceptible to flooding and UHI effects. To enhance resilience, the study proposes structural, nature-based, and technology-driven adaptation strategies, including improved drainage, sponge city concepts, and IoT-based climate monitoring. These findings provide essential insights for urban planners and policymakers, emphasizing the need for climate-adaptive infrastructure planning and sustainable urban development policies.

Keywords: sustainable transport, climate resilience, urban climate adaptation, impervious surface modelling, spatial analysis.

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1. Introduction

Climate change has become one of the global community's biggest challenges, seriously impacting various sectors, including transportation [1][2]. As cities continue to expand, the increasing demand for mobility and accessibility intensifies carbon footprints, making sustainable transport solutions more crucial than ever [3]. Enhancing urban climate resilience in transportation systems requires integrating climate-adaptive infrastructure, energy-efficient mobility options, and robust emergency response mechanisms [4]. This phenomenon is mainly due to increased greenhouse gas emissions [5][6] from human activities, such as urbanisation and infrastructure development [7][8][9]. The increase in the Earth's average temperature due to anthropogenic actions triggers changes in weather patterns and exacerbates the intensity of environmental disasters, such as floods and heat waves [10], [11]. Extreme weather conditions affect infrastructure resilience and alter travel behaviour, requiring new strategies to enhance urban transport adaptability [12]. International conferences such as the United Nations Framework Convention on Climate Change (UNFCCC), Kyoto Protocol, and the Paris Agreement have emphasised the urgency of global collaboration in addressing the challenges of climate change [13], [14]. These changes drive the need for resilient and adaptive planning, especially in the transportation sector, vulnerable to extreme weather phenomena [15], [16]. Sustainable mobility initiatives, such as electric public transport systems and climate-resilient road materials, are essential components in mitigating these risks [17]**.** For example, physical damage from flooding, extreme temperature rises that accelerate the degradation of infrastructure materials, and operational disruptions have increased maintenance costs and decreased the efficiency of transportation [18][19][20].

Bumi Serpong Damai (BSD) City, with a total area of approximately 7,480 hectares, is one of the largest planned cities in Indonesia. It was built in stages through three phases of development. [8][21]. The first phase, completed in 2007 and administratively located in South Tangerang, covers areas facing significant flooding challenges due to ageing infrastructure that was not designed to handle intensifying extreme rainfall and has inadequate drainage systems [11]. The second phase, which began in 2008 in Tangerang District, experienced heightened urbanisation pressures, such as increased impervious surfaces and the urban heat island (UHI) effect, further exacerbating environmental risks [22][20]. Impervious surfaces refer to urbanized areas—such as roads, buildings, and pavements—that prevent water from naturally infiltrating the soil, leading to increased surface runoff and elevated flooding risks. Areas in BSD City with a greater extent of impervious surfaces and reduced vegetation cover are more vulnerable to transportation disruptions caused by climate change. Meanwhile, the third phase, which began in 2020, provides an excellent opportunity to implement sustainability concepts, such as smart city integration and ecosystem-based design, from the start of development [23].

Each area that has been and is being developed in BSD City faces specific environmental challenges that affect the resilience of transportation infrastructure. Primary transportation infrastructure, such as toll roads and urban road networks, are particularly vulnerable to the impacts of climate change, including physical damage from waterlogging, increased temperatures and disrupted connectivity. [24][25]. This impacts population mobility and economic, social and ecological stability. [10][9].

The analysis shows that integrating technologies such as Geographic Information Systems (GIS) is essential to map areas vulnerable to climate change impacts [10][14][26]. This analysis based on spatial data provides insights for risk-based adaptation planning and climate change scenarios, which can be tailored to the characteristics of each BSD City development area [14][23]. A key research question is how urban climate resilience strategies can be effectively integrated into BSD City's transportation planning to mitigate these risks. This research aims to model the distribution of urban heat Islands (UHI), vegetation change, and impervious surfaces in BSD City to identify transportation sectors and areas most vulnerable to climate change impacts [27][26]. This modelling is the first step in developing adaptation strategies that meet the environmental challenges of each BSD City development area [22][23]. Using a data-based approach, this study's results are expected to serve as a reference for stakeholders in designing sustainable policies that increase the resilience of transportation infrastructure to climate change, especially in rapidly developing urban areas such as BSD City [21][23]. Integrating urban climate resilience principles into transport planning will ensure that BSD City remains adaptive, connected, and environmentally sustainable amid ongoing climate challenges.

2. Methods

This research employs a descriptive-analytical approach, integrating quantitative methods to assess climate change risks to transportation infrastructure in BSD City. The quantitative analysis was conducted through remote sensing data processing using Landsat 5 and 7 imagery for three distinct periods (2002, 2013, and 2023). This data produced land use maps, land cover change, land surface temperature, impermeable surface distribution, and flood-prone areas. Spatial analysis was conducted using Geographic Information Systems (GIS) [28] to map the vulnerability of transportation infrastructure to urban heat islands (UHI) and flooding phenomena. In addition, climate change risk projection simulations[29] Were conducted based on short-term (2030) and long-term (2050) scenarios using climatological data from BMKG.

The research phase began with problem formulation, which focused on the primary issue of vulnerability to climate change impacts on transportation infrastructure. Flood risk in BSD City was identified as one of the main challenges caused by inadequate drainage systems and high run-off due to increased built-up area. The UHI phenomenon is another challenge, mainly due to the significant reduction in vegetation area during urban expansion in the second and third phases of BSD City development. This study examines land use change over three periods (2002, 2013, and 2023) to understand its influence on the vulnerability of transportation infrastructure.

The research utilized secondary data, including Landsat 5 and 7 imagery for land use mapping, surface temperature, and impermeable surface distribution. Geographical data, such as drainage maps and infrastructure reports, supported flood risk analysis, while climatological data from BMKG provided historical and projected climate scenarios. BSD City was chosen due to its rapid urbanization, increasing climate vulnerability, and diverse land cover, making it suitable for UHI and flood risk studies. GIS-based spatial analysis enabled detailed risk mapping.

This study aims to model environmental risks in BSD City, focusing on UHI, vegetation change, and impermeable surfaces, to support climate adaptation strategies. Limitations include potential errors in remote sensing data due to atmospheric conditions and uncertainties in climate projections. Nonetheless, the methodology offers a strong framework for assessing infrastructure vulnerabilities and informing urban planning.

3. Results and Discussion

3.1. Overview of the object of research

BSD City, located in Greater Jakarta, Indonesia, is a community-based urban development integrated with various elements of sustainability and environmentally friendly infrastructure. Administratively, BSD City covers two regencies in Banten Province, namely Tangerang Regency and South Tangerang City. With a total area of approximately 7,480 hectares, BSD City is divided into three development phases, each of which has a different size: Phase 1 covering 3,392 hectares, Phase 2 covering 1,671 hectares, and Phase 3 covering 2,417 hectares. The base map included in this report depicts these subdivisions with different colours for each development phase.

As seen in the map in Figure 1, the colours used for each phase indicate the distribution of BSD City's area, which consists of three distinct development phases. The first phase covers 3,392 hectares and is in Tangerang Regency, while the second (1,671 hectares) and third (2,417 hectares) are in South Tangerang City. This division shows how the area is being developed in phases by sustainable development planning.

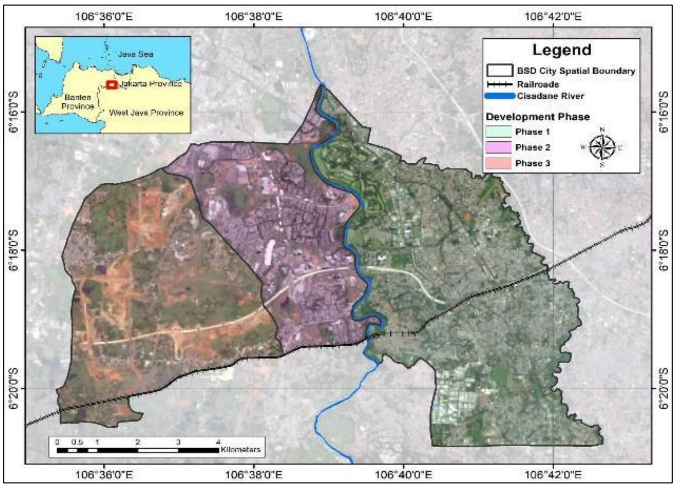


Figure 1. Map of BSD City

With a total area of 7,480 hectares, BSD City is designed to be an urban area that prioritises environmental sustainability, with development that integrates residential, commercial and industrial areas and efficient transportation facilities. Transportation infrastructure, including pedestrian pathways and access to public transportation systems, is continuously developed to support environmentally friendly mobility. For example, in the early phases of development, BSD City has also started to implement 1,021 meters of pedestrian walkways. It continues to develop green open spaces, reaching 319,170 square meters by 2022, to reduce the impact of climate change and improve the quality of the urban environment. This map provides an overview of BSD City's physical division and reflects how spatial planning is prioritised according to the ongoing phases of development.

3.2. Spatial Analysis of Environmental Risk Factors in BSD City

3.2.1 BSD City Land Cover: Changes and Implications

The map, as shown in Figure 2, shows the spatial distribution of land cover in BSD City at three time periods: 2002, 2013 and 2023. Land cover is classified into five categories: Built-up Areas (red colour), which reflect areas with significant infrastructure and urban development; Open Land (orange colour) which indicates areas of construction or land without vegetation; Vegetated Areas (green colour) which include areas with dense vegetation cover such as parks and forests, Sparse Vegetation Areas (light green colour) which include low-density vegetation, and Water Bodies (blue colour) such as rivers, lakes, or other water features.

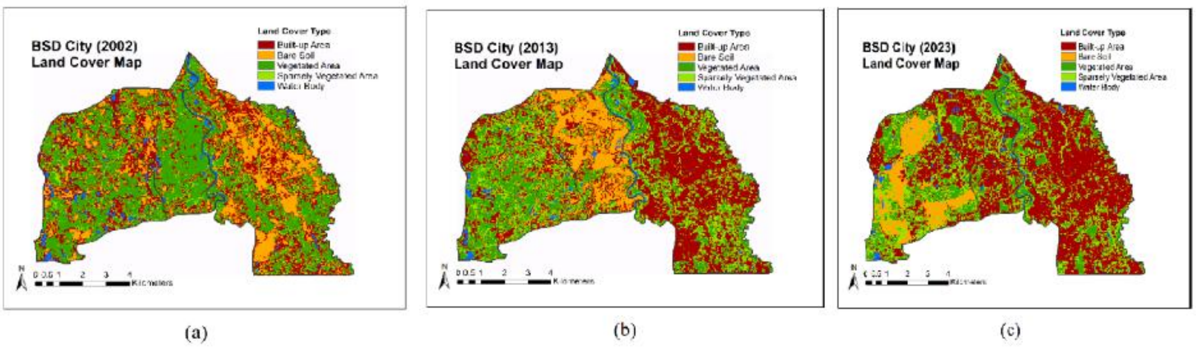
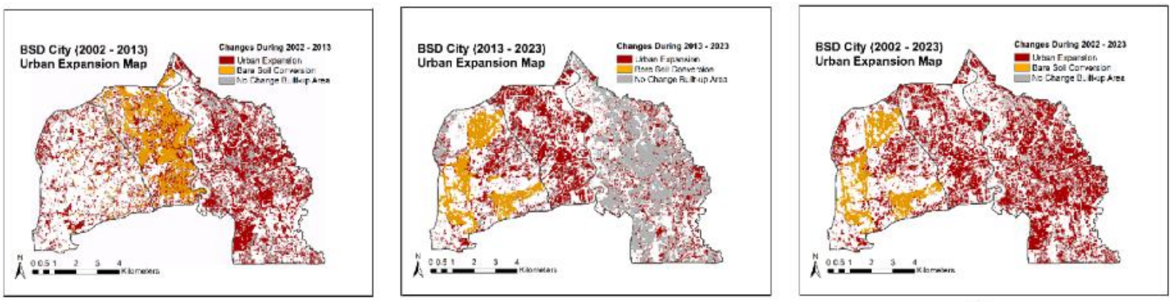


Figure 2. Land Cover Map BSD City

In 2002, the landscape of BSD City was dominated by vegetated areas, reflecting a largely natural and undeveloped environment. Built-up areas and open land were found in small scattered amounts, indicating the early stages of urbanisation. However, in 2013, built-up areas were significantly expanded, especially in the northern and central parts of BSD City, signalling rapid urban development. The area of open land also increased, reflecting the intensity of construction activities during this period. At the same time, vegetated areas began to experience a significant reduction as green spaces were replaced by urban infrastructure.

In 2023, developed areas became the dominant element in the BSD City landscape, reflecting the completion of the overall urbanisation project. Open land areas are reduced as various construction projects are completed. However, the vegetated area continues to decrease, with the remaining green spaces concentrated in planned parks or peripheral regions. In addition, the increase in vegetated areas rarely indicates efforts to integrate green infrastructure into the urban landscape, although more comprehensive implementation still seems to be needed. This land cover change has various environmental implications. The rapid growth of built-up areas represents urbanisation that can increase ecological risks such as Urban Heat Island (UHI) effects, air quality degradation, and loss of natural habitats. The significant decline in vegetated areas also reduces the capacity of the region to mitigate climate, support water infiltration and maintain biodiversity. In addition, the presence of open land areas, which peaked in the transition phase in 2013, can potentially increase the risk of erosion and sedimentation in water bodies. However, the presence of sparse vegetation areas in 2023 reflects efforts to maintain a balance between development and environmental sustainability. The land cover changes in BSD City provide an essential basis for understanding the spatial distribution of environmental risks, such as UHI effects, decreased vegetation, and increased impervious area. The following sections will analyse these risks further.

3.2.2 BSD City Urban Expansion: Dynamics and Implications



(a) (b) (c)

Figure 3. Urban Expansion Map

Figure 3 illustrates the spatial transformation of BSD City over three periods: 2002-2013, 2013-2023, and 2002-2023, categorizing changes into urban expansion, bare soil conversion, and stable built-up areas. The maps highlight the rapid urbanization process, driven by infrastructure development and population growth. Red-coloured regions indicate newly built-up areas, showing a shift from central urbanization to suburban expansion. Quantitative and spatial analysis reveals significant land use changes, emphasizing the increasing dominance of built-up areas over natural landscapes. These findings provide insights into the long-term implications of urban growth on land use and environmental sustainability.

Between 2002 and 2013, the built-up area expanded by approximately 2,202 hectares, primarily in the northern and central regions where accessibility facilitated early development. Bare soil conversion was significant in Phase 2, as land was prepared for further construction projects. This period marked the initial stages of BSD City's transformation, focusing on creating residential and commercial hubs.

The expansion reflected the increasing need for infrastructure to support urban growth. From 2013 to 2023, urban expansion accelerated, adding approximately 3,029 hectares, with a shift toward suburban areas in the south. Phase 3 experienced major land conversion, preparing new zones for large-scale development. The trend indicated a transition from central urbanization to peri-urban growth, driven by rising housing and commercial demands. This expansion phase reinforced BSD City's role as a major urban centre.

Over two decades, BSD City's built-up area increased by 3,664 hectares, significantly altering its natural landscape. This rapid urbanization has environmental consequences, including the Urban Heat Island (UHI) effect and higher flood risks due to reduced green spaces. The decline in permeable surfaces limits water infiltration, leading to greater runoff and potential drainage issues. These factors highlight the urgency of implementing sustainable urban planning strategies. To mitigate these impacts, BSD City needs to integrate green infrastructure, sustainable drainage systems, and eco-friendly urban design. Balancing development with environmental resilience is crucial for maintaining long-term sustainability. Effective planning should focus on minimizing climate-related risks while supporting economic growth. Ensuring a livable urban environment requires proactive policies and strategic land use management.

3.2.3 Analysis of Vegetation Change in BSD City

Analysis of vegetation change in BSD City over three periods, namely 2002-2013, 2013-2023, and 2002-2023, shows significant dynamics in vegetation cover due to urbanisation. From 2002-2013, the decline in vegetation cover was widespread in the central area of BSD City, particularly in what is now known as Phase 2 of the development. Most of these areas underwent conversion to open land or development infrastructure. Meanwhile, some green areas in the south remained consistently vegetated. From 2013 to 2023, the pattern of vegetation loss extends further to the south and west of BSD City, reflecting the development activity centred in the Phase 3 area. This vegetation loss is accompanied by increased vegetation in some small areas, presumably due to reforestation efforts or the planting of green spaces around residential areas and public facilities.

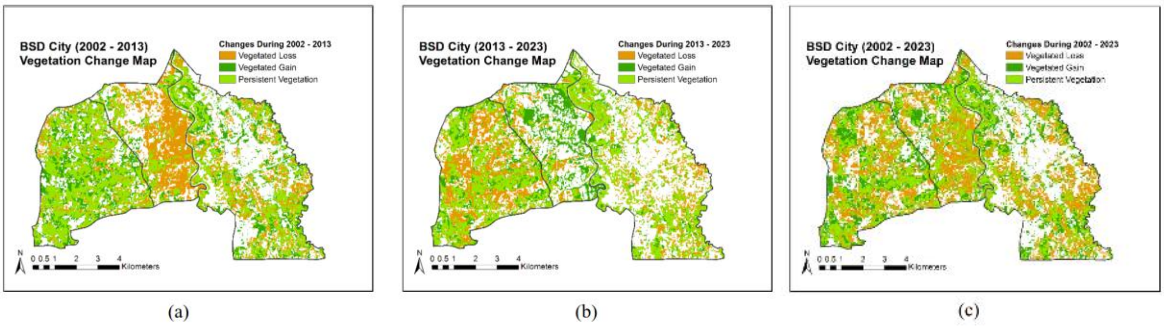


Figure 4. Vegetation Change Map

Over the past two decades (2002-2023), BSD City has experienced a significant loss of vegetation, particularly in areas at the centre of urban development. This loss of vegetation cover reflects the direct impact of urbanisation, with areas of permanent vegetation concentrated in the southern and northwestern parts of the city. This pattern emphasises preserving green spaces to maintain ecosystem balance amid rapid urban development. Vegetation loss in the past two decades has increased the risk of environmental disasters such as flooding, groundwater shortages and deterioration of air quality due to reduced green areas. However, the increase in vegetation in some small regions provides an opportunity to integrate more greening initiatives into the city's development plan.

To compensate for vegetation loss, it is recommended that significant green open spaces be integrated at every stage of BSD City's development. In addition, ecological restoration programs, such as reforestation in degraded areas, need to be implemented to restore environmental capacity. Continuous monitoring through remote sensing technology and spatial analysis is necessary to identify critical areas that require conservation. Sustainable urban development policies also need to be implemented to ensure a balance between urbanisation and environmental conservation. This analysis provides important insights into the impact of urbanisation on the environment and can be the basis for more sustainable development planning in the future.

3.2.4 Urban Heat Island (UHI) Analysis in BSD City

Urban Heat Island (UHI) analysis in BSD City during 2002, 2013, and 2023 as shown in figure 5, shows a significant increase in zones with higher surface temperatures, reflecting the impact of urbanisation on the local microclimate. The UHI effect occurs when urban areas have significantly higher surface temperatures than the surrounding areas. This is due to reduced vegetation, increased impervious surfaces and anthropogenic heat emissions. This study is based on land surface temperature (LST) data obtained from Landsat TIR imagery during the dry season, with minimum and maximum temperatures recorded in BSD City of approximately 22ºC and 32ºC, respectively.

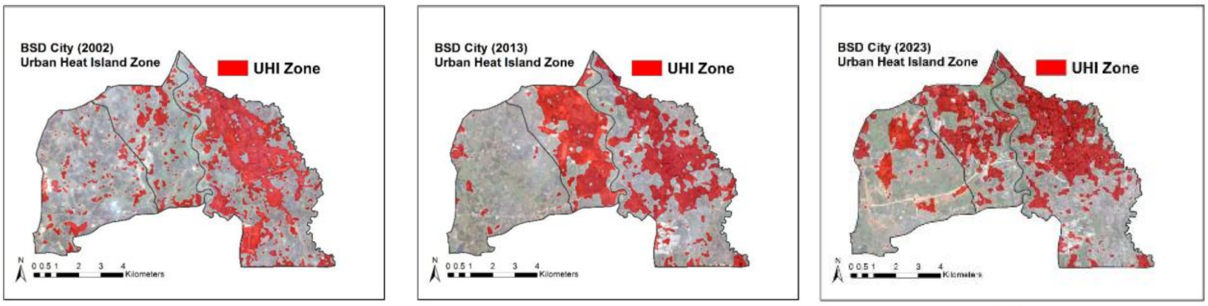


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Figure 5. Urban Heat Island Zone

In 2002, UHI zones were relatively few and mainly concentrated in the central and eastern parts of BSD City. These zones corresponded to areas undergoing early development, where the built environment had replaced vegetation. By 2013, the UHI zones had expanded significantly, particularly in the central and northeastern regions. This expansion reflects rapid urbanisation, with construction activities and increased impervious surfaces further amplifying the UHI effect. The persistence of UHI zones in these areas demonstrates the lasting thermal impacts of urban infrastructure. In 2023, UHI effects spread more widely across BSD City, with significant increases in the southern and western regions. This shift reflects new phases of urban development, highlighting vegetation loss and increased impervious surfaces as the primary factors driving UHI expansion. The observed patterns align with vegetation change analysis, confirming a strong correlation between urbanisation and the intensification of UHI effects.

Integrating sustainable urban planning strategies is essential to mitigate the growing UHI effect. Increasing green spaces, using reflective materials in construction, and implementing innovative urban designs to enhance air circulation can help counteract rising temperatures. Additionally, continuous monitoring of UHI patterns through LST data provides valuable insights for urban planners to balance development with environmental sustainability, ensuring BSD City remains resilient to the negative impacts of urban heat.

3.2.5 Analysis of impervious surface distribution in BSD City

The distribution maps of impervious surfaces in BSD City in 2002, 2013, and 2023 provide an overview of the dynamics of environmental change due to urbanisation. Impervious surfaces, such as roads, sidewalks, buildings, and other concrete areas, are grouped into high, moderate, and pervious surfaces, with water bodies clearly marked. In 2002, the BSD City area was dominated by pervious surfaces, reflecting the early stages of the city's development that still maintained a balance with natural environmental elements. In 2013, significant development began to be seen in Phase 1 with an increase in high impervious surface, while the area of moderate impervious surface also expanded, indicating a more intense expansion of urbanisation. By 2023, massive urbanisation is increasingly evident with the dominance of high impervious surfaces in Phase 1 and parts of Phase 2, while the area of the pervious surface is drastically reduced, reflecting the decrease in green space due to the high intensity of development.

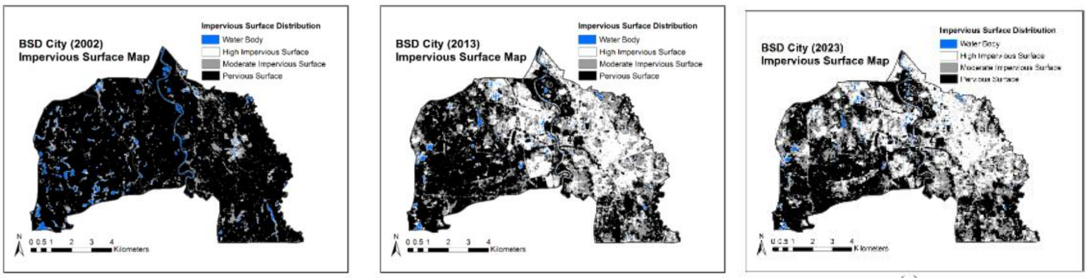

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Figure 6. Impervious Surface Map

These changes have several environmental impacts, most notably an increased risk of flooding due to the reduced ability of the soil to absorb rainwater. Decreased infiltration also disrupts the hydrological cycle, reducing groundwater availability in urban areas. In addition, the loss of natural surfaces contributes to a reduction in biodiversity, as habitats for local flora and fauna are disrupted. Based on spatial analysis, Phase 1 predominates highly impervious surfaces since 2013, reflecting accelerated development compared to Phase 2 and Phase 3, where growth is more gradual.

To mitigate the negative impacts of urbanisation, BSD City needs to integrate environmentally friendly strategies. Measures such as increasing green open spaces around high impervious surface areas, implementing green infrastructure such as rooftop gardens, permeable pavement and bio-swales, and GIS-based analysis to predict flood-prone areas need to be implemented. These strategies help mitigate environmental impacts and support more sustainable spatial planning, thus ensuring a future balance between urbanisation and ecological preservation.

3.3. Analysis of the Transportation Sector and Vulnerable Areas to Climate Change Impacts

3.3.1 Identification of Transportation Sectors and Areas Vulnerable to Climate Change Impacts

Phase 1 of BSD City is highly vulnerable to climate change impacts due to its dense development and extensive impervious surfaces. Minimal stormwater infiltration leads to increased surface runoff, making the area prone to urban flooding during extreme rainfall. Additionally, heavy traffic congestion, especially along Jalan Raya Serpong, exacerbates the Urban Heat Island (UHI) effect, raising surface temperatures and contributing to significant carbon emissions. The lack of green open spaces further heightens environmental risks by reducing water absorption and increasing exposure to air pollution.

Major transportation corridors, particularly Jalan Raya Serpong, are critical areas of concern due to their role as hubs of motorized activity. High traffic intensity from private and public transport contributes to severe air pollution, particularly around train stations and bus terminals. Congestion during peak hours worsens environmental conditions, increasing carbon emissions and directly affecting air quality, public health, and commuter comfort. Without intervention, the negative effects of transportation-related emissions will continue to intensify.

Limited green spaces and inadequate drainage further exacerbate vulnerabilities in Phase 1. With flat topography, the drainage system struggles to manage heavy rainfall, leading to frequent inundation along commercial and residential routes. This disrupts economic activities, hampers mobility, and increases the social and economic burden on residents and businesses. Flooding also affects transportation networks by increasing Vehicle Kilometers Traveled (VKT) and Vehicle Hours Traveled (VHT), as vehicles take longer alternative routes, reducing average speeds by up to 50% in specific flood depths.

Mitigation and adaptation strategies must prioritize these vulnerable areas. In Phase 1, improving drainage capacity, reducing impervious surface dominance, and expanding green spaces are crucial to addressing flood risks and extreme temperatures. In major transportation corridors, electrifying vehicles, constructing bicycle lanes, and integrating green infrastructure along roads can reduce carbon emissions and improve air quality. Special attention should be given to transit hubs and key connectivity routes to enhance BSD City's resilience against climate change impacts.

3.3.2 Adaptation Strategy for Transportation Infrastructure in BSD City

Based on an analysis of BSD City's conditions and relevant literature, an adaptation strategy was designed to enhance transportation infrastructure resilience to climate change. The strategy focuses on green infrastructure, improved drainage, transportation electrification, and reducing impervious surface impacts. These measures target high-risk areas, including Phase 1 and major transportation corridors, to mitigate flooding, temperature rise, and carbon emissions.

1. Green Infrastructure Development: Expanding green spaces, water catchment parks, and bio-swales improves stormwater management, especially in highly impervious areas like Phase 1. In Phases 2 and 3, integrating green corridors and parks from the planning stage can enhance water infiltration and reduce Urban Heat Island (UHI) effects, ensuring a sustainable urban environment.
2. Improved Drainage Capacity: Upgrading drainage systems is crucial, particularly along Jalan Raya Serpong in Phase 1, where channels need expansion to handle extreme rainfall. In Phases 2 and 3, modern drainage integrated with eco-friendly waterways and green spaces can provide long-term flood resilience and climate adaptation.
3. Electrification of Transportation: Transitioning to electric public transport, such as electric buses in Phase 1, can reduce carbon emissions. Strategically placed EV charging stations, especially at transit hubs, will support this shift. Phases 2 and 3 should incorporate sustainable transport systems early, including bicycle lanes and pedestrian-friendly infrastructure for low-emission connectivity.
4. Managing Impervious Surfaces: In Phase 1, permeable materials like porous asphalt can reduce uncontrolled runoff and flood risks. Phases 2 and 3 can prevent excessive impervious surfaces by using permeable materials from the outset in residential and commercial developments, ensuring long-term benefits for transportation safety.
5. Data-Based Risk Management: GIS technology can map high-risk areas prone to flooding, heat, and transport disruptions. Phase 1 requires prioritizing critical routes like Jalan Raya Serpong, while Phases 2 and 3 can use risk-based planning for alternative routes and resilient multimodal transport networks.
6. Redundant Infrastructure Development: Alternative transportation routes are needed to maintain mobility during extreme weather events. In Phase 1, additional pathways can reduce disruptions from flooding or infrastructure failure. Phases 2 and 3 should design redundant connections early to support a resilient, well-integrated urban transport system.

This strategy addresses BSD City's transportation challenges, dividing adaptation efforts by development phases. Immediate action is required in Phase 1 to address existing vulnerabilities, while Phases 2 and 3 offer opportunities for proactive climate adaptation. Using spatial mapping and insights from literature on climate adaptation in transport, this strategy promotes a resilient, sustainable, and well-connected urban mobility system.

4. **Conclusion**

This study concludes that climate change significantly impacts transportation infrastructure in BSD City, primarily through increased flood risk and the urban heat island (UHI) phenomenon. By employing spatial analysis with Landsat 5 and 7 remote sensing data across three time periods (2002, 2013, and 2023), this research provides empirical evidence of the rapid expansion of the built-up area, reduction of vegetation, and high concentration of impermeable surfaces as the main factors exacerbating the vulnerability of transportation infrastructure. In the context of BSD City's three-phase development, Phase 1 (3,392 hectares) was identified as the area with the highest level of vulnerability. The predominance of impermeable surfaces, high traffic intensity, and lack of green open spaces make this area particularly prone to flooding and rising surface temperatures. The eastern region of BSD City, including Serpong District and BSD City CBD, faces significant risks due to inadequate drainage systems and increased run-off. In addition, major transportation infrastructure, such as the BSD toll road and major road networks, is at high risk of physical degradation, potentially leading to severe mobility disruptions and economic instability.

For the Phase 2 area (1,671 hectares), an intermediate development area, the main challenge is ensuring sustainable and connected urbanisation with Phase 1 while integrating climate resilience measures to prevent recurring vulnerabilities. Meanwhile, as a developing area, Phase 3 (2,417 hectares) offers an excellent opportunity to implement solution-based adaptation planning from an early stage. Each phase requires specific adaptation approaches, including improvements to drainage systems, the development of sponge city concepts with green spaces and water catchment parks, and the application of permeable pavement technologies on major roads. In addition, technology-based strategies, such as implementing the Internet of Things (IoT) for real-time risk monitoring and developing low-emission transportation systems such as electric buses and bicycle lanes, are critical to improving transportation resilience throughout the development phase.

This research recommends a comprehensive integration of climate change adaptation strategies into the planning and management of BSD City's transportation infrastructure. Phase 1 requires immediate intervention to mitigate existing risks, while Phase 2 and Phase 3 provide opportunities to implement more systematic, data-driven, and innovative preventive measures. Active participation from developers, local government, and other stakeholders is essential to ensure the success of this strategy. To enhance policy effectiveness, urban planning should incorporate climate-responsive zoning regulations, incentives for green infrastructure investment, and stringent flood risk assessments in new developments.

Despite these contributions, this study has certain limitations. The remote sensing analysis provides valuable insights, but future research should incorporate high-resolution geospatial data and on-ground validation to improve accuracy. Moreover, the study does not account for long-term socio-economic shifts that may influence adaptation effectiveness. Future research should explore multi-scenario climate projections, the role of community-driven resilience initiatives, and cost-benefit analyses of adaptation strategies to strengthen the policy framework. With these measures, BSD City can increase the resilience of its transportation infrastructure to climate change while supporting sustainable urban development.

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