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Article

Structural Vulnerability Assessment of Residential Buildings to Windstorm Hazard with Impact Analysis on Forest Stands: A Case Study from Vojvodina, Serbia

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ABSTRACT

This study presents an indicator-based methodology for assessing the structural vulnerability of individual residential buildings to windstorm hazard. The methodology is based on the Household Sector Approach: CIMDEN 2001 procedure, with parameters adapted to assess the vulnerability of an individual house to windstorm events. In the case of a windstorm event, the structural vulnerability of a house is analyzed through five parameters with assigned weights: roof type, roof construction, roof sides, roof material, number of floors, and doors and windows on non-roof sides. The further classification into low, medium, and high classes is based on construction material and building type, recognizing that some are more vulnerable than others. The material classification is based on the analysis of historical windstorm event outcomes and on material and building types used in specific regions of interest (in this work, Vojvodina, an autonomous province in Serbia). The material and building types in this region are similar across the whole Pannonian Basin. During the development of this methodology, the authors also incorporated the indigenous knowledge and experience of structural damage consequences from two recent supercell storm events on 19 and 21 July 2023. that heavily hit the Novi Sad metropolitan area and caused disruption and destruction of forest areas near the Danube River, power lines, and roofs on schools, individual houses, residential buildings, and companies. The methodology was applied to 50 houses in Bačka Palanka and 11 houses in Begeč, both of which were affected by severe supercell windstorms on 19 and 21 July 2023. Building attributes were derived from Google Street View imagery (2014) and field survey (2026). The resulting vulnerability assessment enabled spatial visualization and comparative assessment in a GIS environment. Buildings with lightweight roof structures, unsealed edges, and multiple openings exhibited higher vulnerability scores, whereas massive masonry structures with sealed roof systems showed greater resistance. Direct windstorm impacts on adjacent riparian forest stands were assessed using Sentinel-2 NDVI change detection, identifying 173.87 ha of severe canopy loss. Beyond immediate damage, the study outlines potential cascading socioecological effects in which household recovery needs may increase pressure on forest ecosystem services.

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The proposed approach provides a screening-level tool for building-scale vulnerability mapping and supports integrated windstorm impact assessment across coupled human-environment systems.

KEYWORDS

Hazards; vulnerability assessment; windstorm disaster; hazard; image analysis; forest; buildings.

1. Introduction

Wind-related hazards such as hurricanes, typhoons, extratropical windstorms, and tornadoes represent one of the most critical threats to the residential building stock, causing widespread physical damage, economic loss, and prolonged community disruption. Within disaster risk assessment, vulnerability is a key component that links hazard intensity to expected damage and loss, typically expressed through vulnerability curves, fragility functions, or probabilistic performance models (Khanduri & Morrow, 2003; Walker, 2011). A growing body of work suggests that vulnerability should not be treated as a static property. Risk models commonly assume that the vulnerability relationship between wind intensity and loss remains constant over time. However, evidence indicates that vulnerability can evolve due to repair, reconstruction, adaptation, and selective removal of fragile building components. Alongside physical vulnerability, research has increasingly emphasized that disaster impacts are shaped by social vulnerability and community resilience (Milenković et al., 2026; Roy, 2025). When disasters hit, local communities are often the first to respond because they are closest to the action and directly impacted by the aftermath (Cvetković et al., 2021). Frameworks that integrate community-level social vulnerability into hurricane wind risk mapping argue that socially vulnerable populations are more likely to reside in physically vulnerable housing and neighborhoods, and therefore resilience-informed decision-making requires combined physical and social vulnerability modeling (Enderami et al., 2022; Rahman et al., 2025). This broadening of vulnerability highlights that the consequences of wind hazards cannot be fully understood through structural fragility alone, but require interdisciplinary modeling that accounts for exposure inequality and recovery capacity. Comparative analysis between elevated houses and slab-on-grade houses in Texas and Florida suggests that elevated houses may experience greater wind damage regardless of roof shape or construction age, indicating that mitigation strategies aimed at flood reduction may unintentionally increase wind exposure and thus alter fragility relationships (Ibrahim et al., 2024). These findings underscore the importance of integrated multihazard thinking when evaluating retrofit and adaptation measures.

Although wind vulnerability modeling has advanced substantially, region-specific evidence remains essential because building typologies and disturbance regimes vary geographically. In Serbia, climate change assessments emphasize increasing exposure to extreme events (e.g., heat waves, storms, droughts), with forests and land-use systems expected to face higher levels of disturbance (Stojanović et al., 2021). For Vojvodina Province, windstorms have been explicitly reported as a recurrent source of damage in poplar clone plantations, indicating that wind disturbance is not episodic but structurally embedded in the regional socioecological system (Pap et al., 2022).

Windstorms are among the most influential abiotic disturbance agents affecting forest ecosystems in Europe and globally, producing not only direct structural damage to trees but also cascades of ecological, economic, and social consequences. Contemporary research increasingly treats windstorm impacts as a systemic phenomenon, in which direct forest damage triggers a chain of secondary effects across multiple dimensions, including forest operations, geomorphology, carbon balance, timber markets, governance responses, and community well-being. This interdisciplinary framing is essential because focusing solely on immediate windthrow and windfall underestimates the long-term disturbance footprint and ignores feedback mechanisms linking ecological damage to human decision-making (Romagnoli et al., 2023).

Recent interdisciplinary syntheses confirm that scientific research has historically concentrated on ecological and biophysical impacts, while the socioeconomic and institutional consequences remain comparatively underexplored. By reviewing over 100 studies, Romagnoli et al. (2023) identified numerous direct and indirect impacts. They emphasized that the cascade relationships between environmental processes and societal dynamics remain poorly analyzed, despite their relevance to post-windstorm management. A more focused socioeconomic review similarly shows that most studies focus on immediate forest-sector stakeholders (e.g., owners, timber industries) but rarely integrate broader governance structures, social values, cultural drivers, and institutional capacity, which ultimately shape recovery and adaptation trajectories (Romagnoli et al., 2022). These findings support the argument that windstorm disturbances must be conceptualized as socioecological events rather than isolated ecological shocks.

Long-term post-disturbance recovery further complicates the assessment of windstorm impacts. Windthrow can temporarily reduce the protective function of forests against secondary hazards such as rockfall, avalanches, and landslides, thereby elevating downstream risk to settlements and infrastructure. Recovery analysis based on canopy height models in the Swiss Alps demonstrates that even after three decades, some structural attributes such as basal area may recover slowly, indicating extended timescales for the restoration of full protective capacity (Moos et al., 2025). This long recovery horizon highlights that windstorm impacts persist far beyond the immediate event and that forest protective services should be treated as dynamic and disturbance sensitive.

Beyond mechanistic understanding, accurate post-event mapping and rapid assessment are critical for operational decision making. Remote sensing has become a key tool in this context because windstorm damage is spatially heterogeneous and often difficult to survey quickly on the ground. Early satellite-based methods combining Landsat imagery with standwise forest inventory data achieved high accuracy in estimating damaged volume and identifying affected areas, demonstrating that low-cost remote sensing can support near-operational monitoring (Jonikavičius & Mozgeris, 2013). Advances in radar remote sensing further enable near-real-time detection, as multitemporal Sentinel-1 SAR approaches have demonstrated the capability to localize and classify windstorm damage severity with high accuracy within days after an event (Tomppo et al., 2021). At the regional scale, multispectral vegetation indices derived from Sentinel-2 have been successfully applied to quantify vegetation condition and spatial patterns of crop response near windbreak systems, supporting the transferability of index-based workflows for post-disturbance vegetation assessment in Vojvodina (Višacki et al., 2024). These developments support the integration of satellite-derived indicators, such as NDVI differencing and SAR backscatter change detection, into modern windstorm impact workflows, especially when rapid planning of salvage operations and safety interventions is required.

Overall, the reviewed literature demonstrates that windstorm disturbances must be interpreted as complex socioecological events generating direct forest damage and multidimensional indirect impacts. Effective mitigation, therefore, requires combining stand-level vulnerability modeling, remote sensing-based rapid damage assessment, and policy-oriented crisis management frameworks that recognize long-term recovery dynamics, market instability, and institutional capacity limitations (Romagnoli et al., 2023; Gardiner et al., 2013; García-Jácome et al., 2025). These findings provide a strong scientific basis for integrating structural vulnerability mapping of built assets with remote sensing-based forest damage detection, thereby enabling a more comprehensive assessment of windstorm consequences across coupled human-environment systems.

Windstorms represent a significant hazard for low-rise residential buildings in the Pannonian Basin, where typical construction practices and roof configurations influence wind-induced damage mechanisms. Within disaster risk reduction (DRR) frameworks, risk is commonly conceptualized as a function of hazard, exposure, and vulnerability, moderated by coping capacity (UNDRR, 2017; Thywissen, 2006).

Hazard refers to the probability and intensity of potentially damaging wind events, exposure to assets in hazard-prone areas, and vulnerability, i.e., the susceptibility of those assets to damage. While vulnerability may evolve due to reconstruction or socioeconomic change, it can be assessed through observable structural characteristics. Coping capacity and resilience influence the extent to which communities can absorb impacts and recover following a disturbance (Villagrán, 2006).

In this study, the focus is placed on the structural vulnerability component at the individual building scale. The objective is to develop and apply a weighted indicator-based methodology, adapted from the Household Sector Approach (CIMDEN, 2001), to classify residential buildings into low, medium, and high vulnerability categories and to enable spatial comparison within the study area.

2. Methods

This study adopts a building-scale structural vulnerability approach within a disaster risk reduction context. Rather than performing a full quantitative risk analysis, the analysis isolates the structural vulnerability component using characteristics derived from observable construction attributes.

The methodological framework consists of three interconnected components:

(i) development and application of a weighted indicator-based structural vulnerability assessment for individual residential buildings, adapted from the Household Sector Approach (CIMDEN, 2001); (ii) characterization of the July 2023 high-intensity windstorm events affecting the study area; and (iii) satellite-based assessment of direct forest damage using Sentinel-2 imagery.

Hazard information is used to contextualize the assessment, but is not coupled with probabilistic loss estimation. Structural vulnerability is therefore interpreted as a relative susceptibility index under a high magnitude windstorm scenario, reflecting construction typology and roof system integrity rather than observed post-event damage.

2.1. Study area

The study was conducted in the Autonomous Province of Vojvodina (northern Serbia), located within the Pannonian Basin. The region is characterized by flat topography, exposure to severe convective windstorms, and predominantly low-rise masonry residential buildings with tiled or metal roof systems.

Two settlements were selected to represent contrasting settlement structures:

- Bačka Palanka, an urban environment with continuous street frontage and relatively uniform residential typology;
- Begeč, a rural settlement composed mainly of detached single-family houses and auxiliary agricultural structures.

Both settlements are situated near the Danube River and share comparable climatic conditions and construction practices. This spatial configuration allows for comparative assessment of structural vulnerability under similar environmental exposure while accounting for differences in settlement morphology.

2.2. Windstorm hazard generation

The analyzed disturbance was associated with two severe convective windstorm events on 19 and 21 July 2023, which affected the Novi Sad metropolitan area and the Danube River corridor in northern Serbia. According to the European Severe Storms Laboratory (ESSL, 2023), the system exhibited supercell development and derecho-type characteristics, producing long-track convective windstorm events across parts of Central and Southeastern Europe.

Within the study area, the event caused extensive windstorm-related damage to residential buildings, power infrastructure, and riparian forest stands. The windstorm is therefore treated as a high-intensity scenario used to contextualize both the structural vulnerability assessment and the satellite-based forest damage analysis.

Figure 1 presents the 3-hour probability forecast of severe convective activity issued one day prior to the first event (18 July 2023, 00:00 UTC), illustrating the synoptic-scale conditions preceding the disturbance (ESSL, 2023).

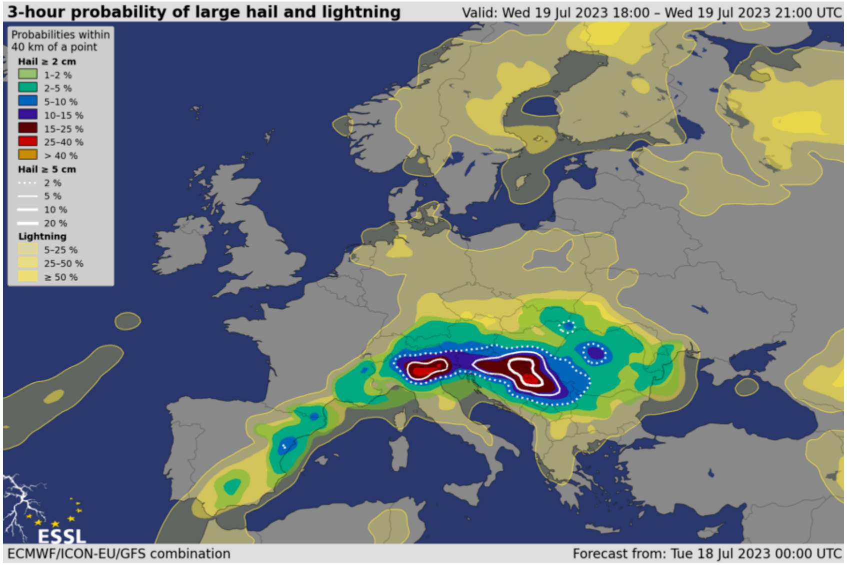

Figure 1. Graphical representation of the 3-hour probability of large hail and lightning for the European continent. Forecast from 18 July 2023, 00:00 UTC, one day before the first storm from 19 July 2023. ESSL (2023), https://www.stormforecast.eu/ [accessed 08.02.2026.]

2.3. Sampling strategy and temporal constraints

A total of 61 residential buildings were evaluated: 50 in Bačka Palanka and 11 in Begeč. In Bačka Palanka, buildings were systematically assessed along a continuous street segment, covering the full street frontage, to ensure spatial consistency and comparable exposure conditions within a uniform urban setting. In Begeč, buildings were selected based on the visibility of roof and facade elements required for indicator classification. Although not strictly probabilistic, the selection aimed to capture representative residential typologies within the rural settlement context, taking into account the experience of previous windstorm events.

Structural attributes were primarily derived from Google Street View imagery dated September 2014. The analyzed windstorm events occurred in July 2023, introducing a temporal mismatch between building documentation and hazard occurrence. Potential modifications to individual structures during the intervening period cannot be excluded. However, field observations conducted in February 2026 in Begeč indicated that dominant roof typologies, facade configurations, and construction systems remained largely unchanged.

The resulting vulnerability assessment, therefore, also represents a structural susceptibility assessment, reflecting typical building characteristics rather than documented post-event damage conditions.

2.4. Structural vulnerability assessment methodology

2.4.1. Indicator selection

Structural vulnerability was evaluated using six indicators representing building components relevant to wind-induced damage mechanisms in low-rise residential structures:

1. Roof type
2. Roof construction
3. Roof sides
4. Roof material
5. Number of floors
6. Doors and windows on non-roof sides

The selected indicators reflect structural characteristics that affect resistance to wind uplift forces, load transfer mechanisms, roof detachment potential, and internal pressure amplification. Their selection was based on established wind damage mechanisms in low-rise buildings and on observed structural failures during regional windstorm events.

2.5. Introduction to Household Sector Approach: CIMDEN 2001 Methodology

In a different approach, the author has developed a procedure to assess four types of vulnerabilities associated with the housing sector at the local level: physical or structural, functional, social, and economic. In this method, each type of vulnerability is measured using parameters directly related to the vulnerability in question, and the different options commonly available in communities for these variables are classified into three ranges: low, medium, and high. The overall vulnerability is expressed in arbitrary units and classified into three ranges according to a predefined table (Table 1). In this case, it is important to recognize several aspects:

- In this model, physical or structural vulnerability is expressed according to the present condition of the house. It addresses the elements that could lead to damage or destruction in the event of an incident.
- The method has been adapted to handle different hazards. Adaptation to different hazards is made by recognizing the impact of the hazard on the various components of the house.
- The indicators display explicitly or directly the vulnerability of the household through the four types of vulnerabilities. It assumes that different options can be classified as having higher or lower degrees of vulnerability, and computes a value based on the assigned weights for each considered parameter.
- The indicators do not show how vulnerability depends on the magnitude of the hazard. The method is based on the assumption of a very high-magnitude event, but it cannot cope with small-magnitude events.
- The vulnerability assessment can be employed to assess the vulnerability of a single house, but can be aggregated at the community, municipal, provincial, and national levels. Figure 24 and Figure 25. displays the structural vulnerability assessment of 7. Jula Street in Bačka Palanka urban settlement and Partizanska Street in Begeč rural settlement. Houses have been classified and identified as low-vulnerable (green), medium-vulnerable (yellow-orange), and highly-vulnerable (red).
- The method identifies options to reduce the degree of vulnerabilities explicitly. However, it has been constructed for specific regions of the world (construction materials and techniques present in one region, for example). Its extrapolation to other regions of the world will need adaptation.
- The method requires a specific survey at the household level to gather information on the four types of vulnerabilities within the housing sector for each house (Villagrán, 2006).

Thus far, the method has been applied in rural communities in Guatemala to address earthquakes, landslides, and volcanic eruptions (Villagrán, 2004; 2005).

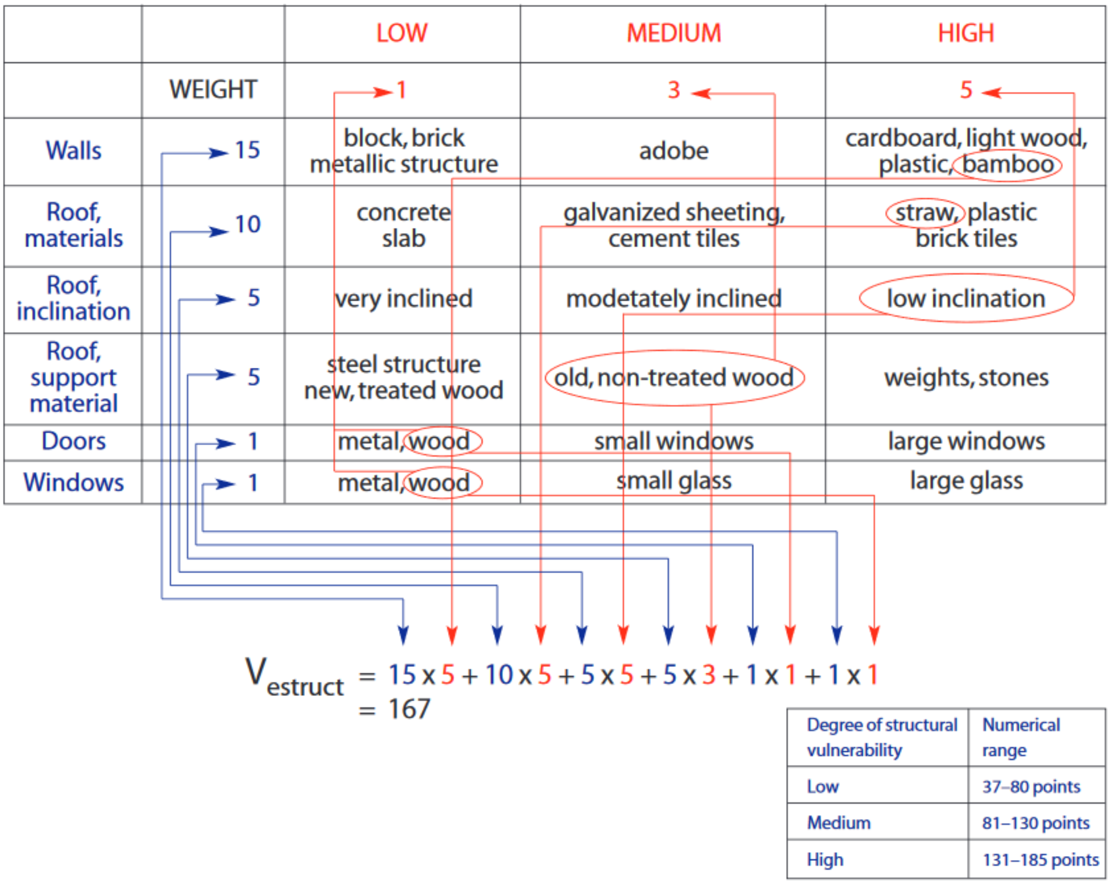

Figure 2. Matrix to assess the structural vulnerability of a house in case of volcanic eruptions. Vulnerability is assessed via indicators based on construction materials for different structural elements of a house (Villagrán, 2006).

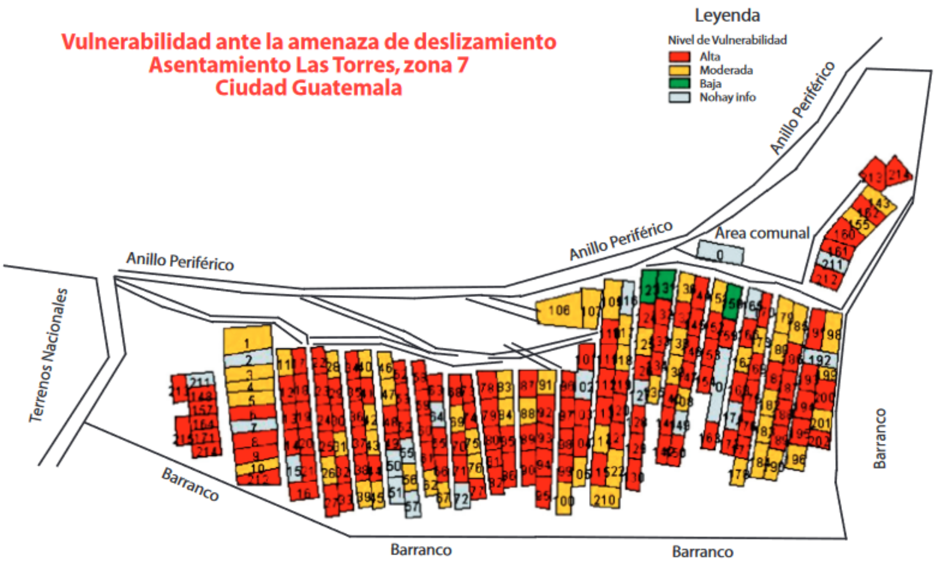

Figure 3. Vulnerability of houses in the Las Torres urban settlement in Guatemala City (Perez, 2001).

Pilot efforts in Guatemala to assess various types of hazards enable comparison of vulnerabilities across different communities. As in the previous case, indicators of structural vulnerability are constructed from the construction materials used for walls, floors, and roofs, considering their susceptibility to failure, thereby provoking damage to the infrastructure.

2.6. Methodology for Structural Vulnerability Assessment of Residential Buildings in Case of Windstorm Hazard

Table 1. Matrix to assess the structural vulnerability of a house in case of a windstorm event.

		LOW	MEDIUM	HIGH
	WEIGHT	1	3	5
Roof type	15	- Roof with four sides (Hip, Dutch, Jerkin-head, Pyramid, and Mansard roof) - Flat Roof	- Roof with two sides with doors and win-dows for attic entrance on one of the non-roof sides (Gambrel, Curved, Saltbox, Butterfly, and Dormer Roof) - Roof without doors with little windows for ventilation	- Roof with two sides with open spaces for doors and windows for attic entrance on one of the non-roof sides - Roof with connected outdoor terrace (Bonnet Roof) - Roof with one side (Skil-lion and Sawtooth Roof)
Roof construction	10	- Entirely closed roof without any hollow places between walls and roof (roof tiles on the edges of the roof sealed with plaster and metal rakes) - Roof ridges sealed with plaster	- Non-closed roof with-out doors and windows on non-roof sides or with closed doors and windows on the non-roof sides - Roof ridges are sealed with plaster, but the roof tiles on the edges of the roof are not sealed - Metal roof ridges	- Non-closed roof with open doors and windows on the non-roof sides - Roof tiles on the edges of the roof are not sealed, with or without metal rakes - Roof ridges not sealed with plaster
Roof sides	5	- Two brick rows with plaster as bonding ma-terial, with reinforced brick supporting pillars - No roof sides	- Reed and plaster with internal reinforcement with wooden laths - Oriented strand board (OSB) with internal rein-forcement and plaster - Applied styrofoam with plastic armored grid and plaster on both above cases	- Reed and plaster with-out reinforcement - One brick row without reinforcement - Poor quality of doors and windows on the non-roof sides
Roof material	5	- Roof tiles with vapor-permeable foil	- Metal roof with va-por-permeable foil - Roof tiles without va-por-permeable foil - Asphalt roof shingles	- Metal roof without va-por-permeable foil - Biber plain roof tile - Asbestos roof sheets - Bitumen roof sheets
Number of floors	1	- One	- Two	- Three or more
Doors and windows on non-roof sides	1	- Polyvinyl Chloride (PVC) and wooden doors and windows with double glass and good holders on the sides - Without doors and windows - Without glass	- Bad placement of new doors and windows instead of older ones, due to the destruction of the old brick construc-tion, and bad placement of new bricks with the older ones	- Polyvinyl Chloride (PVC) and wooden doors and windows with one glass and bad holders on the sides - With little open win-dows for ventilation

2.7. Indicators

2.7.1. Roof Type

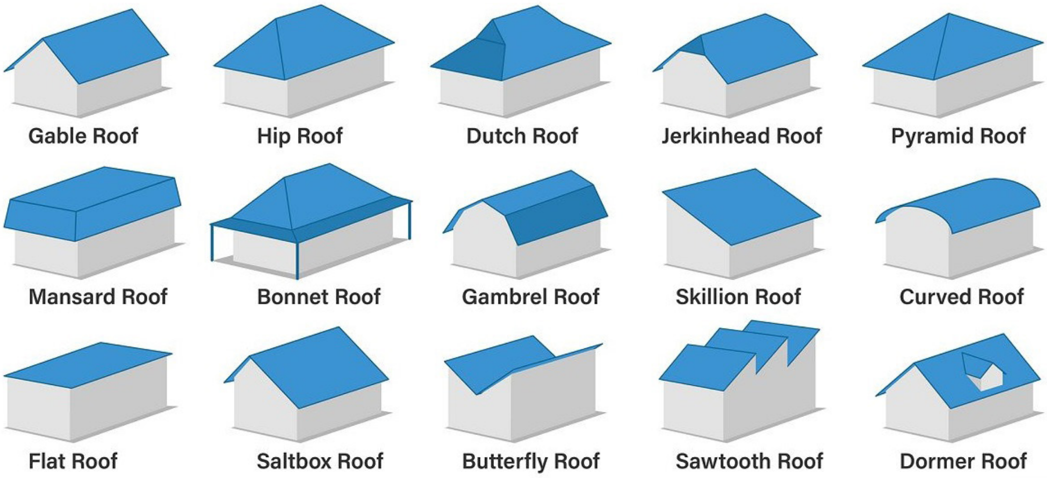

Figure 4. Different types of roofs. (Roof Gnome)

2.7.2. Roof Construction

Figure 5. Entirely closed roof without any hollow places between walls and roof, which prevents the uplifting of the whole or some parts of the roof by a windstorm.

Figure 6. Entirely closed roof without any hollow places between walls and roof. Google Street Imagery 2014.

Figure 7. Metal roof ridges are tightened to the roof tiles. This is one of the most exposed and vulnerable parts of the roof during a windstorm event.

Figure 8. Non-closed roof with closed doors and windows on the non-roof sides. During the windstorm, all roof tiles will be uplifted on this exposed roof construction example.

Figure 9. Closed roof with open doors and windows on the non-roof sides. One of the most frequently observed damages after the windstorms was to houses with open doors and windows on the non-roof sides. In this example, it can uplift the whole roof construction. Google Street Imagery 2014.

Figure 10. Roof ridges and roof tiles on the edges of the roof are not sealed, and there are no metal rakes on the edge of the roof. During the windstorm, the first row of roof tiles will be uplifted, creating more space for wind to enter beneath the tiles and blow them away. Google Street Imagery 2014.

Figure 11. Roof ridges sealed with plaster. This step will prevent the blowing of roof ridges and expose the top of the roof to wind.

Figure 12. Roof tiles and ridges sealed with plaster. Google Street Imagery 2014.

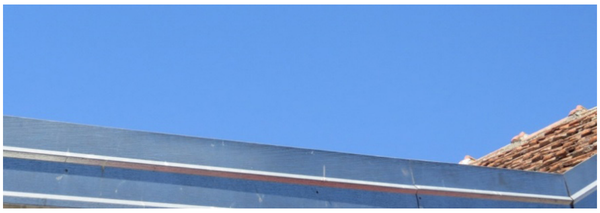

Figure 13. Roof with metal rakes. Wider metal rakes will prevent direct wind impact on the roof edges, preventing the lifting of the first row of roof tiles or other roof materials.

2.7.3. Roof Sides

Figure 14. One brick row without reinforcement, with little open windows for ventilation. The wind can enter through this window and lift a few roof tiles, opening the space for more to blow off. In the case of a one-brick row without internal reinforcement, it can be demolished by a high wind gust. Google Street Imagery 2014.

Figure 15. Wooden door, reed, and plaster without reinforcement.

2.7.4. Roof Material

Figure 16. Asbestos roof sheets. This type of roof material is highly vulnerable because it is fragile and can be lifted in one piece during windstorms.

Figure 17. Biber plain roof tile. This type of roof material is highly vulnerable because it is fragile, lightweight, and can be easily lifted during windstorms. Google Street Imagery 2014.

Figure 18. Bitumen roof sheets. This example shows the highly vulnerable roof with irregular bitumen roof sheets damaged by the sun. Google Street Imagery 2014.

Figure 19. Metal roof without vapor-permeable foil. In the case of a metal roof, wind blows, and the permeable foil prevents water from entering the house.

Figure 20. Regular roof tiles.

2.7.5. Number of Floors

Figure 21. Houses with two floors and a gable roof type. Houses with two, three, or more floors will have a greater probability of suffering damage during windstorm events. Google Street Imagery 2014.

2.7.6. Doors and Windows on Non-roof Sides

Figure 22. Polyvinyl Chloride (PVC) door and window with double glass and a metal door with good holders on the sides. Roof sides with two brick rows with plaster as bonding material, with reinforced brick supporting pillars. This type of roof side is highly resistant to damage from windstorm events.

2.8. Satellite image analysis for the assessment of direct forest windstorm disaster consequences

For the direct windstorm image analysis, we used Sentinel-2 L2A atmospherically corrected surface reflectance (Bottom of Atmosphere – BOA) products for normalized difference vegetation index (in further text NDVI) generation and for comparison of NDVI from different dates for assessment of forest damage intensity from windstorms on 19 and 21 July, 2023.

NDVI is a widely used index that quantifies vegetation greenness and can indicate vegetation health and density. It is calculated as the ratio of the near-infrared (NIR) to the red band. Positive values generally correspond to vegetation, with higher values reflecting healthy, dense vegetation.

NDVI = (NIR – RED) / (NIR + RED)

For Sentinel-2:

NDVI = (B8 – B4) / (B8 + B4)

The color-infrared images before and after the windstorm disaster were produced together with pre- and post-windstorm disaster NDVI images. The difference between pre- and post-NDVI images was presented with a new layer with a different color palette, which further produced a new vectorized layer of complete forest destruction. Two images taken from the ground were also presented to visualize the consequences of the forest windstorm better.

Important information is that the post-event damage is also previously examined by producing a change detection map for the Begeč settlement and confirming changes through a field survey and various ground images after the windstorm events. The next step in the ongoing research was the development of this windstorm structural vulnerability assessment methodology, which can be further explored by examining the detailed indirect impacts of forest windstorm events. (Jeftic et al., 2024)

3. Results

The following results present the structural vulnerability assessment of 50 houses to windstorm hazard in Bačka Palanka and 11 houses in the Begeč settlement. As an example, the structural vulnerability calculation for house no. 22 in Bačka Palanka urban settlement is provided below. The overall score of 79 points classifies house no. 22 as having low structural vulnerability to windstorm hazards.

Vestruct = 15 x 3 + 10 x 1 + 5 x 1 + 5 x 3 + 1 x 3 + 1 x 1 (Figure 23) = 79

Table 2. Degree of structural vulnerability

Degree of structural vulnerability	Numerical range
Low	37-80 points
Medium	81-130 points
High	131-185 points

		LOW	MEDIUM	HIGH
	WEIGHT	1	3	5
Roof type	15	- Roof with four sides (Hip, Dutch, Jerkinhead, Pyramid and Mansard roof) - Flat Roof	- Roof with two sides with doors and windows for attic entrance on one of the non-roof sides (Gambrel, Curved, Saltbox, Butterfly and Dormer Roof) - Roof without doors with little windows for ventilation	- Roof with two sides with open spaces for doors and windows for attic entrance on one of the non-roof sides - Roof with connected outdoor terrace (Bonnet Roof) - Roof with one side (Skillion and Sawtooth Roof)
Roof construction	10	- Entirely closed roof without any hollow places between walls and roof (roof tiles on edges of the roof sealed with plaster and metal rakes) - Roof ridges sealed with plaster	- Non-closed roof without doors and windows on non-roof sides or with closed doors and windows on the non-roof sides - Roof ridges sealed with plaster but roof tiles on edges of the roof not sealed - Metal roof ridges	- Non-closed roof with open doors and windows on the non-roof sides - Roof tiles on edges of the roof not sealed and with or without metal rakes - Roof ridges not sealed with plaster
Roof sides	5	- Two brick rows with plaster as bonding material with reinforced brick supporting pillars - No roof sides	- Reed and plaster with internal reinforcement with wooden laths - Oriented strand board (OSB) with internal reinforcement and plaster - Applied styrofoam with plastic armored grid and plaster on all two above cases	- Reed and plaster without reinforcement - One brick row without reinforcement - Poor quality of doors and windows on the non-roof sides
Roof material	5	- Roof tiles with vapor permeable foil	- Metal roof with vapor permeable foil - Roof tiles without vapor permeable foil - Asphalt roof shingles	- Metal roof without vapor permeable foil - Biber plain roof tile - Asbestos roof sheets - Bitumen roof sheets
Number of floors	1	- One	- Two	- Three or more
Doors and windows on non-roof sides	1	- Polyvinyl Chloride (PVC) and wooden doors and windows with double glass and good holders on sides - Without doors and windows - Without glass	- Bad placing of new doors and windows instead of older ones by destruction of old brick construction and bad placing of new bricks with older ones	- Polyvinyl Chloride (PVC) and wooden doors and windows with one glass and bad holders on sides - With little open windows for ventilation

$$Vestruct = 15 \times 3 + 10 \times 1 + 5 \times 1 + 5 \times 3 + 1 \times 3 + 1 \times 1$$
$$= 79$$

Figure 23. Matrix to assess the structural vulnerability of house no. 22 in case of windstorm hazard.

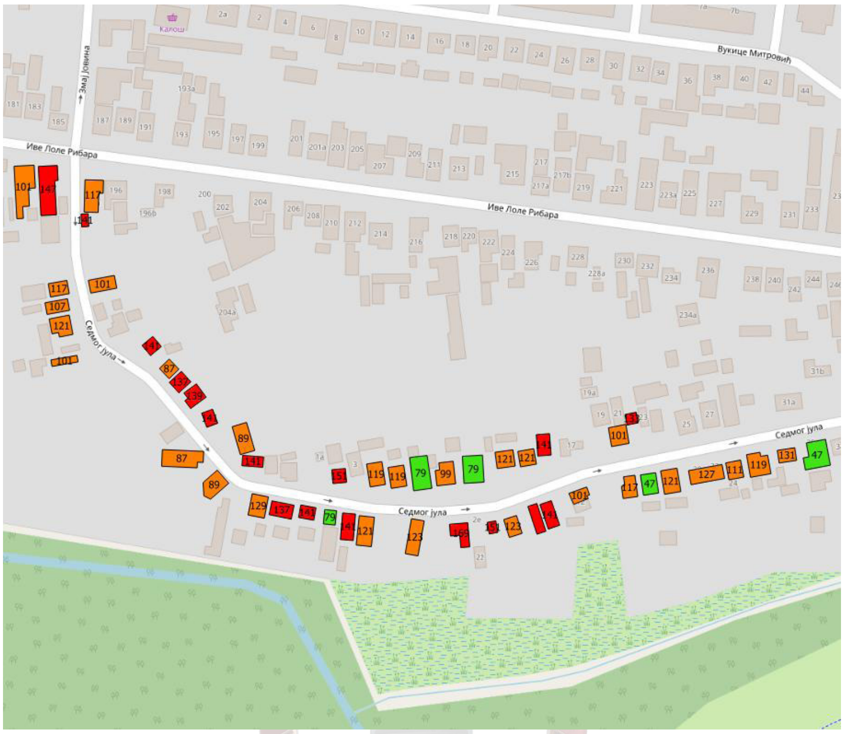

Figure 24. Structural vulnerability of 50 houses in the 7. Jula Street in Bačka Palanka urban settlement in the case of a windstorm hazard. Each color and number represents the degree of structural vulnerability. Data was obtained from Google Street View imagery from September 2014.

Figure 25. Structural vulnerability of randomly chosen 11 houses in the Partizanska Street in the Begeč rural settlement in the case of windstorm hazard. Each color and number represents the degree of structural vulnerability. Data were obtained through a field observation survey conducted on the ground on 8 February 2026.

3.1. Windstorm direct impacts on forest stands

The direct impacts are immediate consequences of windstorm events, such as windfall, windthrow, and wind bending of large forest stands. The following image analysis shows an example of forest windstorm damage to Čerevićka ada and other nearby Danube River forests. The analysis was done by using Sentinel-2 images from 18 July 2023, one day before the first windstorm event on 19 July 2023, and from 28 July 2023, seven days after the second windstorm event on 21 July 2023. The color-infrared images before and after the windstorm disaster were produced together with pre-and post-windstorm disaster NDVI images. The difference between pre- and post-NDVI images was presented as a new layer using a different color palette, which was then used to produce a new vectorized layer showing complete forest destruction. The area under complete forest destruction shown in Figure 31 is 173.87 ha.

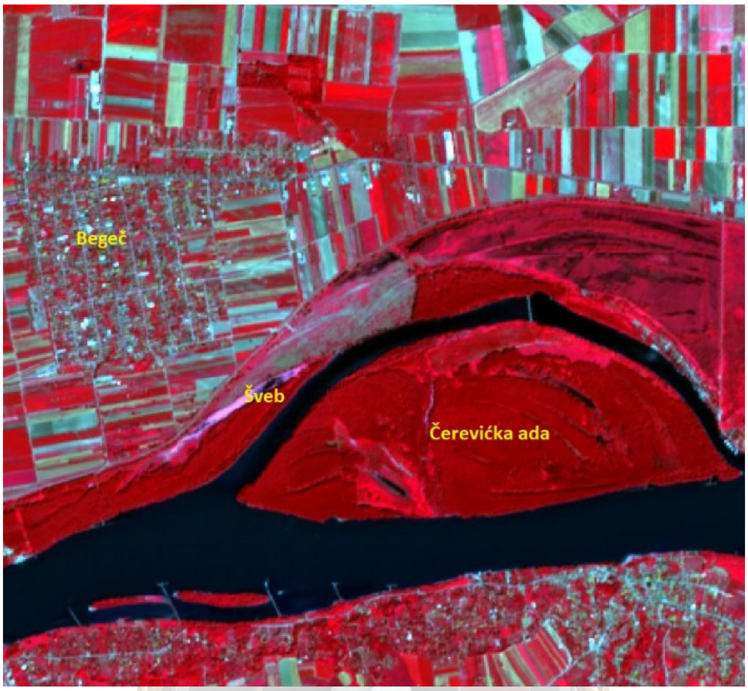

Figure 26. Sentinel-2 color infrared image of the Danube River forested area on 18 July 2023, before the windstorm events on 19 and 21 July 2023. (Contains modified Copernicus Sentinel-2 data 2023)

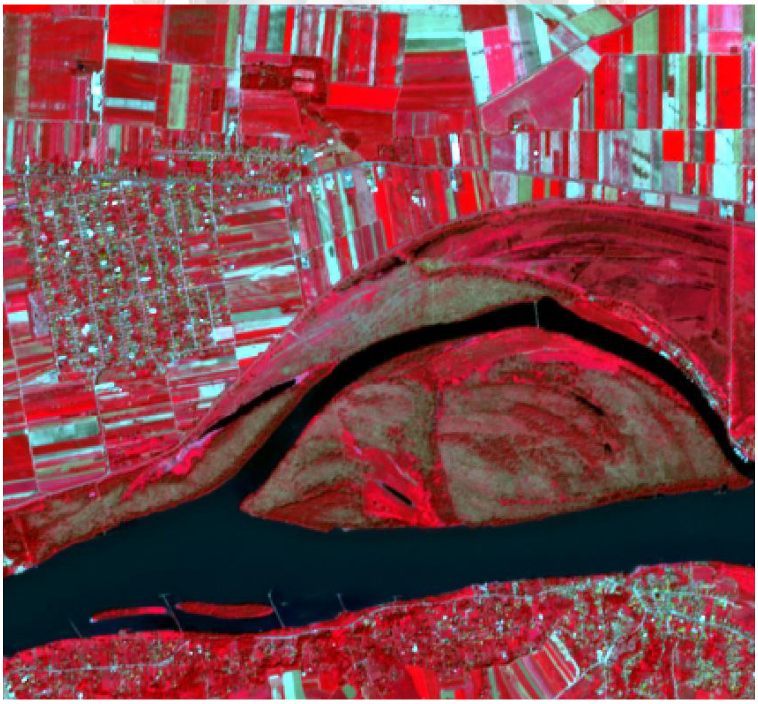

Figure 27. Sentinel-2 color infrared image of the Danube River forested area on 28 July 2023 after the windstorm events. (Contains modified Copernicus Sentinel-2 data 2023)

Figure 28. Normalized difference vegetation index (NDVI) of the Danube River forested area on 18 July 2023, before the windstorm events on 19 and 21 July 2023. (Contains modified Copernicus Sentinel-2 data 2023)

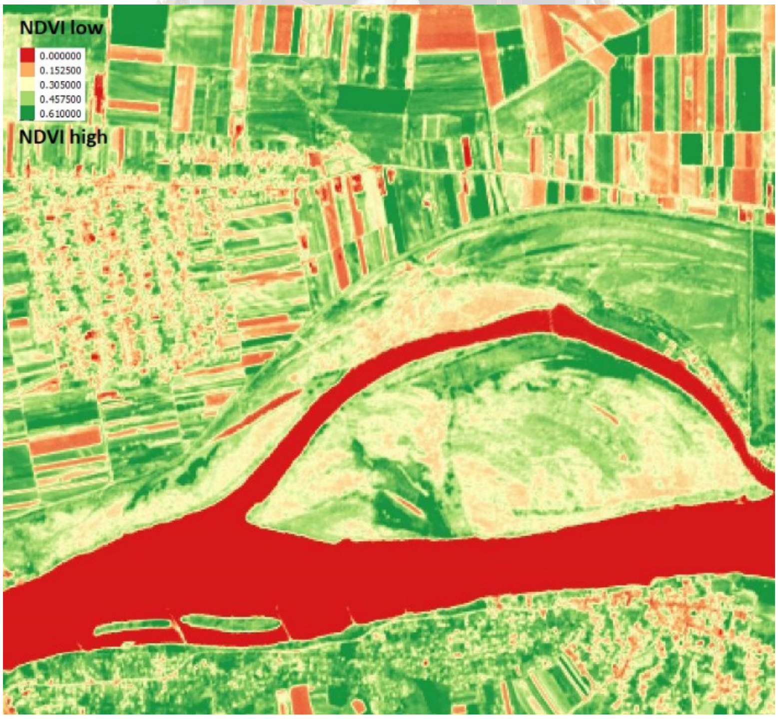

Figure 29. Normalized difference vegetation index (NDVI) of the Danube River forested area on 28 July 2023 after the windstorm events. (Contains modified Copernicus Sentinel-2 data 2023)

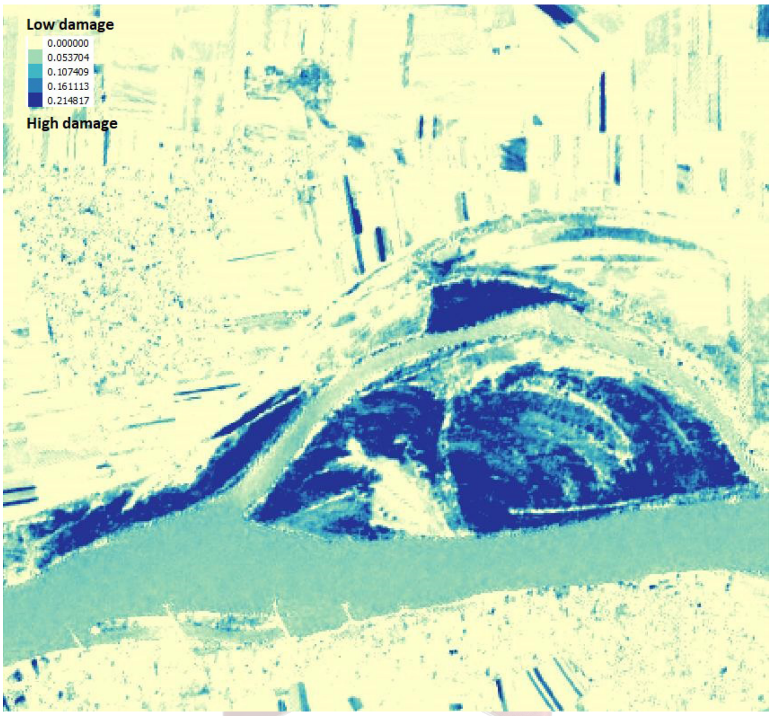

Figure 30. Difference between pre and post-disaster NDVI images (dNDVI = preNDVI – postNDVI) with applied color palette. Dark blue represents the destruction of forested areas (windfall, windthrow, and wind bending), while light-blue turquoise represents partial damage (broken tree branches, damaged canopy). (Contains modified Copernicus Sentinel-2 data 2023)

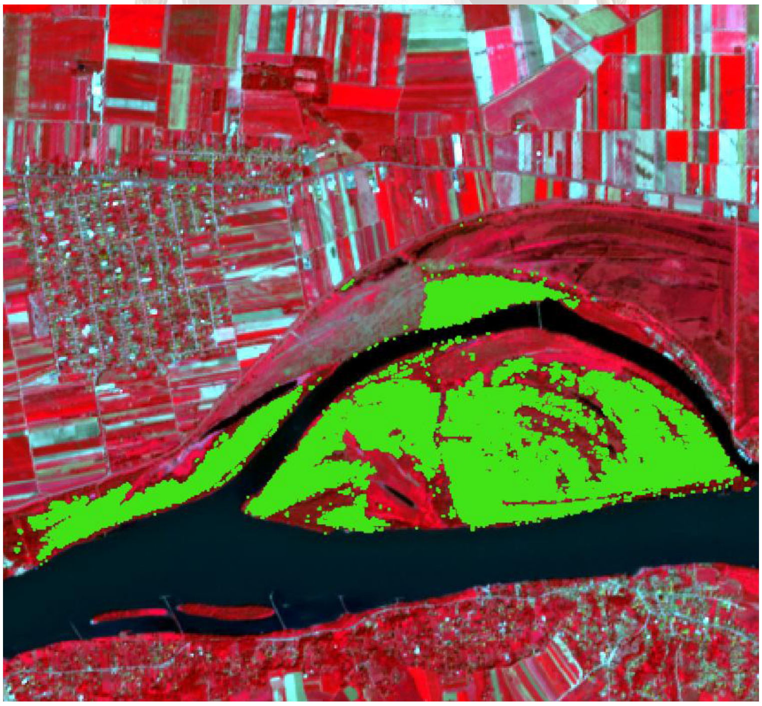

Figure 31. The vectorized layer, colored in green, represents the destruction of forested area (windfall, windthrow, and wind bending). Calculated damaged area is 173.87 ha. (Contains modified Copernicus Sentinel-2 data 2023)

Figure 32. Ground image of forest destruction taken on 23 July 2023, near the Šveb location in Begeč.

Figure 33. Ground image of Čerevićka Ada forest taken on 27 September 2020.

Figure 34. Ground image of Čerevićka Ada forest taken on 7 February 2026.

3.2. Windstorm indirect impact on forest stands

Indirect impacts are usually manifested through increased stress and pressure on forest ecosystem services over a prolonged period. The analysis will cover the short progression of vulnerability by examining the household response to windstorm disasters and the subsequent pressure on forest ecosystem services. Some households in our example that were hit by a windstorm hazard cannot afford to pay for energy for food preparation and heating during the winter months. The majority of those households then turn to wood heating, which is sometimes provided through official wood purchases or through individual households' tree-logging activities in nearby forests. In both cases, the pressure on the forest is the same. As storms often hit in the summer months, they also disrupt the income-generating activities of individual households during the agricultural season and other seasonal jobs. They must repair their damaged roofs, usually by taking credit or spending their savings, which they have set aside for winter when there are not as many seasonal jobs, especially in communities that largely depend on agricultural services. Also, after the supercell windstorm events on 19 and 21 July that hit Bačka Palanka and Begeč settlement, many people in Begeč took the roofs from their storage and agricultural machinery buildings to cover their residential buildings. To this day, many storage and agricultural machinery buildings are still without roofs. Another possible impact on household incomes is the future potential unemployment of local people due to nearby forest logging activities, as the forested areas along the Danube River are at their lowest level. The indirect impact is evident today and will be evident in the future because people always rely on affordable wood for the winter months from the nearby Danube forest, which two supercell windstorm events have now destroyed. They must now turn their savings to usually more expensive wood from other locations, which accounts for transportation costs. The surviving trees and forests from both windstorm events are under greater pressure to be logged, especially forests within agricultural areas that are usually left and intended as wildlife habitats.

4. Discussion

4.1. Structural vulnerability assessment

The most important note is that Bačka Palanka indicators were extracted from Google Street View imagery dated September 2014, demonstrating the use of this tool for rapid disaster risk reduction activities, while the windstorm event occurred in July 2023. The February 2026 field observations in Begeč suggest that dominant roof typologies and facade configurations persist over time in this region. It must be stated again that indicators do not show how vulnerability depends on the magnitude of the hazard. The method is based on the assumption of a very high-magnitude event, but it cannot cope with small-magnitude events.

This temporal mismatch between the two surveys is also relevant for any implied connection between observed 2023 damage and the vulnerability assessment, because the study does not include a formal building-level damage dataset for calibration or validation. Similar studies stress that vulnerability is not purely static; it can evolve after events due to repair, reconstruction, and selective replacement of weak components (Trojand et al., 2025; Mehdizadeh et al., 2023).

The paper currently uses the July 19 and 21, 2023, windstorm events because of the widespread disruption to both social and environmental processes and the authors' indigenous knowledge of these events. Since no local wind speed hazard map or intensity metric is explicitly coupled to each building, the study cannot produce quantitative risk (expected loss).

4.2. Direct forest impacts derived from Sentinel-2 and linkage to the vulnerability narrative

The Sentinel-2 NDVI differencing workflow provides a transparent, replicable way to delineate and quantify areas of severe canopy loss following the July 2023 windstorms, producing an estimate of complete forest destruction (173.87 ha) in the examined Danube riparian forest segment. This supports the extensive literature showing that windstorms are a dominant disturbance agent in European forests and that rapid, spatially explicit assessment is essential for operational response (Gardiner et al., 2013; Jonikavičius & Mozgeris, 2013; Tomppo et al., 2021).

4.3. Indirect impacts and cascading relationships between households and forests

The indirect-impact narrative proposed here is consistent with an interdisciplinary framing of windstorm effects as cascading socioecological dynamics rather than purely biophysical damage. Reviews emphasize that indirect impacts and cascade relationships between environmental damage and socioeconomic behavior are often underanalyzed, even though they shape long-term resilience (Romagnoli et al., 2023; Romagnoli et al., 2022).

4.4. Methodological value and transferability

The main methodological contribution is an operational procedure for creating house-level vulnerability maps using accessible visual data (Google Street View and field surveys) and standard GIS workflows. This is directly aligned with indicator-based approaches that prioritize scalability and interpretability (Papathoma-Köhle et al., 2023; Massarra et al., 2021). The approach is likely transferable across the Pannonian Basin, where construction traditions are similar, but transferring to regions with different roof typologies, construction practices, or building codes would require adapting indicator categories and local calibration against observed damage.

5. Conclusion

The vulnerability has several dimensions: physical or structural, environmental, economic, social, political, technical, ideological, ecological, institutional, educational, health-related, cultural, etc. This paper aimed to present, for the first time, a methodology for assessing the structural vulnerability of individual households' residential buildings in the event of windstorm hazard in a region known to be highly vulnerable to such events. The further objective was to present the direct and indirect impact of windstorm events on forested areas on which those households depend. The interconnection between the individual structural household vulnerability and the environmental vulnerability of forests is presented in a short analysis, which can be examined in detail in the future by including the other vulnerability components related to windstorm hazard.

This paper presents a practical methodology for assessing and mapping the structural vulnerability of individual residential buildings to windstorm hazard in Vojvodina, Serbia, using a weighted indicator matrix derived from the Household Sector Approach (CIMDEN, 2001) and adapted for wind-relevant building characteristics. Application to the sampled housing stock in Bačka Palanka and Begeč demonstrates that overall relative vulnerability can be consistently classified into low, medium, and high categories using observable roof and facade properties and visualized in QGIS software for a better display of high, medium, and low structural vulnerability of individual houses and comparison among them. This type of digitally obtained structural vulnerability map, together with a hazard map, plays a crucial role in all stages of a disaster management cycle.

In parallel, the study demonstrates a satellite-based procedure using Sentinel-2 NDVI change detection to delineate direct windstorm impacts on riparian forest stands, quantifying a mapped footprint of severe canopy loss. This provides spatial evidence of windstorm-driven forest disturbance relevant to operational planning and understanding broader disturbance consequences.

Beyond direct damage, the study outlines a plausible cascading impact pathway in which household recovery needs following windstorm damage (repair costs, seasonal income disruption) can increase reliance on forest ecosystem services (fuel wood, informal logging), thereby amplifying pressure on already disturbed forest stands. This socioecological linkage is consistent with recent interdisciplinary syntheses that emphasize the importance of indirect impacts and governance dimensions in post-windstorm management. During the development of this methodology, the authors also incorporated the indigenous knowledge and experience of structural damage consequences from two recent supercell storm events on 19 and 21 July 2023. that heavily affected the Novi Sad metropolitan area and caused disruption and destruction of forest areas near the Danube River, power lines, and roofs on schools, individual houses, residential buildings, and companies. This type of knowledge, obtained from previous and present windstorm disaster consequences, helped in a large way to effectively determine the most vulnerable elements of the individual houses, thereby informing methodology adaptation to windstorm hazard.

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