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Flood Risk and Logistics Adaptation: A Structural Analysis of Route Choice and Inventory Buffers Among SMEs

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ABSTRACT

Recurring flooding has become a structural operating risk for firms in monsoon-affected regions, yet empirical evidence on how small and medium-sized enterprises (SMEs) adapt logistics decisions under such conditions remains limited. This study examines how flood exposure shapes route choice and inventory buffering among SMEs in Terengganu, Malaysia. Using firm-month panel data and a structural estimation framework, the analysis models route choice and inventory buffers as jointly determined adaptation mechanisms rather than independent responses. The findings show that higher flood exposure increases the likelihood of avoidance routing, indicating that route choice functions as a deliberate risk-management strategy. While flood exposure is associated with higher inventory buffers in naïve models, this effect attenuates once route choice endogeneity is addressed. Structural estimates reveal a substitution mechanism whereby routing flexibility reduces reliance on costly inventory buffers. These results highlight that SME resilience under climate risk reflects constrained optimization between avoidance and absorption strategies, with important implications for managerial practice and infrastructure policy in flood-prone regions.

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1. Introduction

Climate-related flooding has become an increasingly persistent challenge for logistics operations worldwide. Unlike sudden catastrophic events, floods often occur repeatedly and generate continuous uncertainty regarding transportation reliability, delivery schedules and inventory availability (Kahn et al., 2021; United Nations Office for Disaster Risk Reduction [UNDRR], 2023). As climate-related disruptions become more frequent, firms are required to adapt operational decisions to maintain service continuity and minimise disruption-related losses.

Recent supply chain studies recognise climate risk as an operational challenge that affects transportation performance, logistics costs and supply chain reliability (Addoum et al., 2020; Pankratz & Schiller, 2023). However, much of the existing evidence focuses on large organisations with greater financial resources and operational flexibility. Small and medium-sized enterprises (SMEs) face substantially different conditions. Limited working capital, restricted storage capacity, and fewer logistics alternatives reduce their ability to absorb disruptions and increase their vulnerability to recurring environmental risks (OECD, 2023).

In flood-prone environments, SMEs typically rely on two operational responses. The first is route adaptation, where firms select alternative transportation routes to avoid disruption. The second is inventory buffering, where additional inventory is maintained to protect against replenishment uncertainty and delivery delays (Chopra & Sodhi, 2014; Ambulkar et al., 2015). While both strategies contribute to operational resilience, they require different resource commitments and may involve important trade-offs for resource-constrained firms.

Terengganu provides an appropriate setting for examining these adaptation decisions. The state experiences regular monsoon flooding that frequently affects transportation networks and logistics activities. SMEs operating in retail distribution, wholesale trade, agro-based industries, and light manufacturing depend heavily on road transportation and are therefore particularly exposed to disruptions in transportation reliability. Under such conditions, logistics adaptation becomes a recurring operational necessity rather than a temporary recovery response.

Despite growing interest in climate-related supply chain resilience, two important gaps remain. First, existing studies commonly examine route choice and inventory buffering as independent responses to disruption. Second, there is limited firm-level evidence explaining how SMEs in flood-prone environments allocate resources between alternative adaptation strategies. As a result, the interaction between transportation flexibility and inventory redundancy remains insufficiently understood.

This study addresses these gaps by examining how flood exposure influences route choice and inventory buffering among SMEs in Terengganu. Drawing on Resource-Based View and Organizational Resilience Theory, the study conceptualises route adaptation and inventory buffering as interconnected resilience mechanisms. A structural estimation approach is employed to capture the behavioural relationship between avoidance-based and absorption-based adaptation strategies.

The study contributes to the literature in three ways. First, it extends climate-related logistics research by examining flood risk as a recurring operational condition rather than an isolated disruption event. Second, it introduces a structural perspective that models route choice and inventory buffering as jointly determined adaptation decisions. Third, it demonstrates how SMEs balance logistics flexibility and inventory redundancy when responding to recurring flood exposure. These findings provide practical insights for managers and policymakers seeking to strengthen supply chain resilience in climate-vulnerable regions.

2. Literature Review

This study is grounded in the Resource-Based View (RBV), which argues that organizational performance depends on the ability of firms to develop and deploy valuable resources and capabilities under changing environmental conditions (Barney, 1991). Within logistics and supply chain management, RBV has been widely used to explain how operational capabilities contribute to resilience, adaptability, and competitive advantage (Hitt et al., 2016).

In flood-prone environments, SMEs frequently operate with limited financial resources, restricted storage capacity and constrained access to advanced logistics technologies. As a result, firms must allocate scarce resources strategically to maintain operational continuity during disruption periods. Route flexibility, information visibility and inventory management capabilities represent important organizational resources that support adaptation under recurring environmental uncertainty (Brandon-Jones et al., 2014).

From an RBV perspective, route adaptation and inventory buffering are strategic capabilities that enable firms to respond to disruption risk. However, because SMEs often face resource limitations, managers must make trade-offs between competing adaptation mechanisms. Consequently, resilience outcomes depend not only on flood exposure but also on how effectively firms deploy available resources and capabilities (Barney, 1991; Hitt et al., 2016).

Organizational Resilience Theory

While RBV explains the importance of organizational resources, Organizational Resilience Theory explains how firms utilise those resources to absorb, adapt to, and recover from disruptions (Ponomarov & Holcomb, 2009). Resilience literature commonly distinguishes between flexibility and redundancy as two primary adaptation mechanisms (Pettit et al., 2019).

Flexibility refers to the ability to modify operational processes in response to changing conditions. In logistics settings, route adaptation represents a flexibility-based strategy because firms alter transportation pathways to reduce disruption exposure. Redundancy refers to the maintenance of additional resources that absorb disruption impacts. Inventory buffering represents a redundancy-based strategy because firms maintain additional stock to ensure service continuity during periods of uncertainty (Pettit et al., 2019).

Recurring flood events create persistent uncertainty regarding transportation reliability, replenishment schedules and service performance (UNDRR, 2023; Ivanov, 2024). Under such conditions, SMEs continuously adjust operational decisions rather than implementing one-time recovery actions. Because resource constraints often prevent simultaneous investment in multiple resilience mechanisms, SMEs must balance flexibility and redundancy when responding to recurring disruptions (OECD, 2023).

Flood Risk, Route Choice and Inventory Buffers

Floods affect logistics performance primarily by increasing transportation uncertainty and reducing delivery reliability. Even when transportation networks remain accessible, variability in travel time and replenishment performance creates operational challenges for inventory planning and customer service management (Kahn et al., 2021; Ivanov, 2024). Consequently, firms frequently respond to anticipated uncertainty rather than waiting for complete transportation failure.

One common adaptation mechanism involves route choice. Traditional route selection emphasizes transportation cost and travel-time efficiency. Under flood conditions, however, firms increasingly prioritise reliability and disruption avoidance (Lam & Yin, 2022). Research suggests that decision-makers are often willing to accept longer travel distances and higher transportation costs when such adjustments improve predictability and reduce disruption risk (Zhou et al., 2023).

A second adaptation mechanism involves inventory buffering. Inventory serves as a protection mechanism against lead-time variability and replenishment uncertainty by maintaining product availability during disruption periods (Tang, 2006; Chopra & Sodhi, 2014). However, inventory buffering imposes significant financial and storage costs, particularly for SMEs operating under capital constraints.

Recent resilience literature increasingly suggests that flexibility and redundancy function as partially substitutable adaptation mechanisms (Pettit et al., 2019; Ivanov, 2024). Firms may reduce inventory requirements when routing flexibility improves, whereas limited routing alternatives may increase reliance on inventory redundancy. This substitution mechanism highlights the importance of examining route adaptation and inventory buffering as interconnected decisions rather than independent responses.

Theoretical Integration

The integration of RBV and Organizational Resilience Theory provides the foundation for the structural framework developed in this study. RBV explains the internal capabilities that support adaptation, while Organizational Resilience Theory explains how these capabilities are deployed through operational responses.

Within this framework, flood exposure acts as an external trigger that generates uncertainty regarding transportation reliability. Firms subsequently utilise available capabilities to implement resilience strategies. Route adaptation represents a flexibility-based response intended to avoid disruption, whereas inventory buffering represents a redundancy-based response intended to absorb disruption impacts. Because both mechanisms pursue similar resilience objectives, they are expected to interact rather than operate independently.

Accordingly, the study proposes that route choice functions as an endogenous adaptation mechanism linking flood exposure and inventory buffering. Improved routing flexibility is expected to reduce transportation uncertainty and lower the need for inventory redundancy, while limited routing options are expected to increase reliance on inventory buffers.

Conceptual Framework and Hypotheses

The conceptual framework positions flood exposure as the primary external driver influencing SME adaptation behaviour. Route choice represents a flexibility-based response to disruption risk, while inventory buffering represents a redundancy-based response to residual uncertainty. Information access and financial constraints influence the effectiveness of these adaptation mechanisms.

H1: Flood risk perception increases the likelihood of choosing lower-exposure alternative routes.
H2: Flood risk perception is positively associated with inventory buffer levels.
H3: Route choice partially mediates the relationship between flood risk perception and inventory buffers.

3. Research Methodology

Research Design and Empirical Strategy

This study employs a quantitative panel-data design to examine how SMEs adapt logistics operations under recurring flood risk. The analysis focuses on two interconnected adaptation mechanisms: route choice as an avoidance strategy and inventory buffering as an absorption strategy. Because these decisions are potentially interdependent, a structural estimation framework is adopted to account for simultaneity and endogenous adaptation behaviour (Train, 2009; Wooldridge, 2010).

The empirical setting consists of SMEs operating in Terengganu, Malaysia, where recurring monsoon flooding regularly affects transportation reliability and logistics operations. The unit of analysis is the firm-month observation, enabling the study to capture changes in adaptation behaviour across different flood exposure conditions.

Study Setting and Sampling

The target population comprises SMEs engaged in retail distribution, wholesale operations, and light manufacturing activities that depend on regular road transportation. Firms were selected using stratified random sampling based on industry sector and geographical district to ensure representation across different logistics environments within Terengganu (Creswell & Creswell, 2018; Sekaran & Bougie, 2020).

The sampling frame was developed using records obtained from SME Corporation Malaysia, local business directories, and district business registration databases. Eligible firms were required to:

1. Operate as SMEs under Malaysian definitions.
2. Conduct regular inbound or outbound logistics activities.
3. Maintain basic inventory management records.
4. Experience at least one monsoon season during the observation period.

As presented in Table 1, the study targeted approximately 200 SMEs observed over a 36-month period. After data screening, quality checks, and panel attrition, the final analytical sample consisted of 192 SMEs and 5,928 firm-month observations.

Table 1. Sample Design and Panel Structure

Component	Description
Industry Sectors	Wholesale Distribution, Retail Operations, Light Manufacturing
Geographical Coverage	Kuala Terengganu, Dungun, Kemaman, Besut, Marang, Setiu, Hulu Terengganu
Target SMEs	200
Final SMEs	192
Observation Period	36 Months
Final Firm-Month Observations	5,928
Unit of Analysis	Firm-Month

Data Sources

Data were assembled from three sources:

1. Firm surveys capturing flood risk perception, information access, logistics arrangements, and financial constraints.
2. Operational records containing inventory positions, delivery performance, replenishment outcomes, and route utilisation.

3. Geo-coded flood exposure data comprising flood occurrence, rainfall intensity, and transportation disruption indicators.

These datasets were integrated at the firm-month level using locality and district identifiers.

Variable Operationalisation

Table 2. Variable Operationalisation Framework

Variable	Operational Measurement	Scale
Flood Exposure	Composite index based on flood days, rainfall exceedance and road disruptions	Continuous
Route Choice	1 = avoidance route selected; 0 = standard route selected	Binary
Inventory Buffer	Days of inventory on hand beyond normal replenishment requirements	Continuous
Lead-Time Variability	Coefficient of variation of lead time	Continuous
Information Access	1 = access to traffic and warning systems; 0 = otherwise	Binary
Financial Constraint	Composite liquidity and financing index	Continuous
Demand Volatility	Rolling coefficient of variation of demand	Continuous
Logistics Outsourcing	1 = outsourced logistics; 0 = internal logistics	Binary

Table 2, summarize the route choice represents a flexibility-based adaptation mechanism in which firms deliberately utilise alternative transportation routes to reduce flood exposure. Inventory buffering represents a redundancy-based adaptation mechanism measured through days of inventory on hand. Flood exposure is measured using a composite index that captures both environmental conditions and transportation disruption intensity.

Structural Adaptation Framework

Drawing upon Resource-Based View and Organizational Resilience Theory, the study conceptualises logistics adaptation as a sequential process. Flood exposure generates operational uncertainty that influences route adaptation behaviour. Route choice subsequently affects replenishment reliability and inventory buffering decisions. Accordingly, route choice is treated as an endogenous adaptation mechanism linking environmental risk and inventory policy.

Flood Exposure
↓
Route Choice (Avoidance Strategy)
↓
Lead-Time Reliability
↓
Inventory Buffers (Absorption Strategy)

Supporting Factors:
Information Access, Financial Constraints, Demand Volatility, Logistics Outsourcing

Figure 1. Structural Adaptation Framework

The framework assumes that SMEs allocate limited resources between flexibility-based and redundancy-based resilience strategies. Consequently, route choice and inventory buffering are modelled as jointly determined decisions rather than independent outcomes.

Model Specification

Route Choice Equation

The probability of selecting an avoidance route is estimated using a panel logit specification with firm and month fixed effects:

$$RouteChoice\_it = \beta 0 + \beta 1 FloodExposure\_it + \beta 2 X\_it + \alpha\_i + \lambda\_t + \varepsilon\_it$$

where X represents control variables, α_i denotes firm fixed effects, and λ_t represents month fixed effects.

Inventory buffering is estimated as:

$$InventoryBuffer\_it = \gamma 0 + \gamma 1 FloodExposure\_it + \gamma 2 RouteChoice\_it + \gamma 3 X\_it + \alpha\_i + \lambda\_t + u\_it$$

Because route choice may be endogenous, a control-function approach is employed following Rivers and Vuong (1988) and Wooldridge (2010). Predicted route-choice probabilities and generalized residuals obtained from the first-stage route model are incorporated into the inventory equation to address simultaneity bias.

Estimation Procedure

The empirical analysis follows four stages:

1. Estimation of the route choice model.
2. Estimation of baseline inventory buffer models.
3. Structural correction for route-choice endogeneity using the control-function approach.
4. Decomposition of direct and indirect effects to identify the mediating role of route adaptation.

Firm fixed effects are included to control for unobserved time-invariant heterogeneity, while month fixed effects account for seasonality and common macroeconomic shocks (Imbens & Wooldridge, 2009; Wooldridge, 2010).

Robustness Checks

Several robustness checks were conducted to assess the stability of the findings. These include alternative flood exposure measures, alternative inventory buffer specifications, multinomial route-choice models, placebo tests during non-monsoon periods, and stable-sample estimations. Consistent findings across specifications provide confidence in the robustness of the reported results.

4. Findings

Sample Construction and Panel Structure

Table 3 provides a summary of the analytical dataset after the data screening and validation procedures. The dataset was assembled at the firm-month level and examined for eligibility, data completeness, and consistency of firm identifiers across reporting periods. Following data cleaning and panel validation, the final sample comprised 192 SMEs and 5,928 firm-month observations. The resulting panel remained sufficiently large to support fixed-effects estimation and structural modelling.

Table 3. Sample Construction and Panel Structure

Step	Description	Firms	Firm-Months
1	Eligible SMEs approached	420	–
2	Met inclusion criteria and consented	280	–
3	Provided baseline survey and operational records	214	6,870
4	Non-missing route choice and inventory measures	198	6,102
5	Final analytical sample	192	5,928

The final panel captures substantial variation in flood exposure across multiple monsoon cycles, allowing the analysis to identify within-firm adaptation behaviour under changing environmental conditions.

Descriptive Statistics

Table 4. presents summary statistics for the principal variables. Inventory buffers averaged 18.4 days, indicating that many SMEs maintained additional stock as a precaution against operational disruptions. Approximately 36% of firm-month observations involved avoidance routing, suggesting that route adaptation is a common response to flood-related uncertainty.

Table 4. Descriptive Statistics

Variable	Mean	SD	P25	Median	P75
Buffer (Days)	18.4	11.2	10.0	16.0	24.0
Route Avoidance	0.36	0.48	0.00	0.00	1.00
Flood Exposure	0.00	1.00	-0.62	-0.10	0.55
Lead-Time Variability	0.23	0.14	0.12	0.20	0.31
Information Access	0.41	0.49	0.00	0.00	1.00
Demand Volatility	0.19	0.10	0.12	0.17	0.24

The results suggest substantial variation in logistics conditions across firms and time periods, supporting the suitability of panel-data estimation.

Correlation Analysis

Flood exposure exhibits a positive association with both avoidance routing and inventory buffering. The positive relationship between lead-time variability and inventory buffers is consistent with inventory management theory, suggesting that replenishment uncertainty remains a key determinant of safety-stock decisions.

Table 5. Correlation Matrix

Variable	Buffer	Route Avoid	Flood Exposure	Lead-Time CV	Info Access
Buffer	1.00	0.12	0.21	0.33	-0.08
Route Avoid	0.12	1.00	0.28	0.19	0.17
Flood Exposure	0.21	0.28	1.00	0.24	0.05
Lead-Time CV	0.33	0.19	0.24	1.00	-0.02
Info Access	-0.08	0.17	0.05	-0.02	1.00

Table 5 reports pairwise correlations among the key variables. Reliability and validity assessments indicated satisfactory measurement quality for all multi-item constructs. Cronbach's alpha values exceeded 0.70, composite reliability values exceeded 0.80, and average variance extracted values exceeded 0.50, indicating acceptable reliability and convergent validity (Hair et al., 2022).

Route Choice Under Flood Exposure

The first stage of the analysis examined whether flood exposure influences avoidance-routing behaviour. Route choice was estimated using a panel logit model with firm and month fixed effects. Flood exposure consistently increases the likelihood of avoidance routing across all model specifications. The interaction term indicates that information access strengthens adaptation behaviour, suggesting that firms with better visibility are more capable of adjusting routes during periods of elevated flood risk. These findings support H1, which proposes that flood risk increases the probability of selecting lower-exposure transportation routes.

Table 6. Panel Logit Model for Avoidance Route Choice

Variables	(1) Baseline	(2) + Controls	(3) + Interactions
Flood Exposure	1.42***	1.36***	1.31***
Information Access	1.18**	1.15*	1.12
Flood Exposure × Information Access	–	–	1.12*
Demand Volatility	–	1.21**	1.19**
Outsourcing	–	1.08	1.06
Firm FE / Month FE	Yes	Yes	Yes
Observations	5,928	5,928	5,928

*Note: $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$*

Inventory Buffering Under Flood Exposure

The second stage estimated the relationship between flood exposure and inventory buffers using fixed-effects regression models. The positive coefficient for flood exposure indicates that SMEs increase inventory buffers when facing greater disruption risk. However, the effect declines substantially once lead-time variability is introduced, suggesting that transportation reliability serves as an important mechanism linking flood exposure and inventory behaviour. The findings provide preliminary support for H2, which predicts a positive relationship between flood risk and inventory buffering.

Table 7. Fixed-Effects Regression of Inventory Buffers

Variables	(1) FE Only	(2) + Controls	(3) + Lead-Time CV
Flood Exposure	1.85***	1.54***	0.88*
Lead-Time Variability	–	–	14.2***
Demand Volatility	–	2.90**	1.60
Information Access	–	-0.70	-0.42
Firm FE / Month FE	Yes	Yes	Yes
Observations	5,928	5,928	5,928
Within R^2	0.06	0.09	0.14

Structural Relationship Between Route Choice and Inventory Buffers

Table 8 presents the results of the structural analysis conducted to address the potential endogeneity of route adaptation. In this analysis, route choice was specified as an endogenous mediator between flood exposure and inventory buffers using a control-function approach.

The findings indicate a significant negative relationship between avoidance routing and inventory buffers, suggesting that SMEs adopting routing flexibility require lower levels of inventory redundancy compared with firms relying primarily on inventory-based protection strategies. Furthermore, the statistically significant control-function residual confirms the existence of endogeneity in naive model specifications and validates the use of the structural estimation approach. Overall, these results support H3 and demonstrate that route choice partially mediates the relationship between flood exposure and inventory buffering.

Table 8. Structural Inventory Buffer Model

Variables	(1) Naïve	(2) Control Function	(3) + Lead-Time CV
Flood Exposure	1.20**	0.62	0.31
Route Avoidance	-2.10***	-2.65***	-1.40**
Control Function Residual	–	1.85**	1.20*
Lead-Time Variability	–	–	11.6***
Firm FE / Month FE	Yes	Yes	Yes
Observations	5,928	5,928	5,928

Direct and Indirect Effects

Table 9 reports the decomposition of the total effect of flood exposure into its direct and indirect components to provide further insight into the adaptation process. The results indicate that flood exposure exerts an overall positive effect on inventory buffers; however, a portion of this effect is mitigated through the use of avoidance routing. This finding suggests that SMEs simultaneously employ flexibility-based and redundancy-based adaptation mechanisms in responding to recurring flood risks, highlighting the complementary roles of route adaptation and inventory protection in enhancing logistics resilience.

Table 9. Effect Decomposition

Effect Component	Estimate
Total Effect of Flood Exposure	+1.20
Indirect Effect via Route Choice	-0.58
Direct Effect	+1.78

Robustness Checks

Several robustness tests were conducted using alternative flood exposure measures, inventory specifications, and route-choice classifications. Additional placebo analyses using non-monsoon periods produced substantially weaker effects. Across all specifications, the direction and significance of the key coefficients remained consistent.

Overall, the findings provide strong support for the proposed structural adaptation framework. Flood exposure influences both route choice and inventory buffering, while route flexibility reduces dependence on costly inventory redundancy. The results suggest that SME resilience under recurring flood conditions is achieved through a dynamic balance between avoidance and absorption strategies rather than through reliance on a single adaptation mechanism.

5. Discussion

Flood Risk as a Reliability Challenge

The findings suggest that recurring flood exposure should be understood primarily as a reliability challenge rather than solely as a physical accessibility problem. Although floods can disrupt transportation networks through road closures and infrastructure damage, the evidence indicates that SMEs are more frequently affected by uncertainty in delivery schedules, replenishment timing, and transportation reliability. Even when roads remain partially accessible, increased variability in travel time and delivery performance creates significant operational challenges for inventory planning and customer service management (Christopher, 2023; Ivanov, 2024).

This finding contributes to the logistics resilience literature by highlighting the importance of reliability risk as a distinct dimension of climate-related disruption. Traditional studies often emphasize accessibility failure and infrastructure interruption as primary disruption outcomes (UNDRR, 2023). However, the present results indicate that firms frequently respond to anticipated uncertainty before transportation networks become completely inaccessible. Consequently, operational adaptation appears to be driven by expectations regarding logistics performance rather than solely by actual disruption events.

The positive relationship between flood exposure and avoidance routing further supports this interpretation. SMEs appear willing to sacrifice transportation efficiency in favour of improved reliability during periods of elevated risk. This behaviour aligns with transportation resilience research, which suggests that decision-makers prioritise predictability and service continuity when operating under uncertain conditions (Train, 2009; Zhou et al., 2023).

Resource-Based View and Organizational Resilience Perspective

The findings provide support for the Resource-Based View by demonstrating that adaptation outcomes depend not only on exposure to environmental risk but also on the availability and deployment of organizational capabilities. SMEs facing similar flood conditions exhibited different adaptation responses depending on their ability to utilise logistics flexibility, information access, and inventory management capabilities. This observation supports the RBV argument that competitive advantage and operational resilience emerge from the effective use of valuable organizational resources rather than from environmental conditions alone (Barney, 1991; Hitt et al., 2016).

The results also reinforce Organizational Resilience Theory, which views resilience as the ability to anticipate, absorb, and adapt to disruptions through multiple operational mechanisms (Ponomarov & Holcomb, 2009). Consistent with resilience theory, SMEs did not rely on a single adaptation strategy. Instead, firms combined flexibility-based and redundancy-based responses depending on the severity of disruption and the availability of resources. This supports the view that resilience is a dynamic capability involving continuous resource allocation and adaptation rather than a static organizational attribute (Pettit et al., 2019; Wieland & Durach, 2024).

The positive influence of information access on routing behaviour further highlights the role of organizational capabilities in supporting resilience. Firms with better access to flood alerts, transportation information, and local logistics intelligence demonstrated stronger adaptation responses. This finding is consistent with prior research identifying visibility and information quality as critical enablers of supply chain resilience (Brandon-Jones et al., 2014; Pettit et al., 2019).

Substitution Between Flexibility and Redundancy

The most significant contribution of this study lies in the identification of a substitution mechanism between route flexibility and inventory redundancy. The structural estimates demonstrate that avoidance routing is associated with lower inventory buffers once endogeneity is addressed. This finding suggests that SMEs can achieve resilience through alternative pathways rather than relying exclusively on inventory accumulation.

The result is consistent with resilience literature that distinguishes flexibility and redundancy as complementary but partially substitutable resilience mechanisms (Pettit et al., 2019; Ivanov, 2024). Route adaptation reduces replenishment uncertainty by improving transportation reliability, thereby lowering the need for costly inventory buffers. Conversely, when routing alternatives are unavailable, firms compensate by increasing inventory holdings to protect service continuity.

This finding extends previous research by demonstrating that adaptation strategies should not be examined independently. Route choice and inventory management form part of an integrated adaptation system in which decisions regarding one resilience mechanism influence the effectiveness and necessity of another. As a result, models that analyse these responses separately may overestimate the direct impact of flood exposure on inventory behaviour while underestimating the role of transportation flexibility.

The findings further suggest that resilience among SMEs is constrained by resource availability. Unlike large organizations that can simultaneously invest in multiple resilience capabilities, SMEs must carefully allocate limited resources across competing adaptation options. Consequently, resilience should be viewed as a portfolio decision involving trade-offs between flexibility, redundancy, and financial sustainability (OECD, 2023).

Practical Implications and Future Research

The findings provide several practical implications for SMEs operating in flood-prone environments. First, route planning should be treated as a strategic resilience activity rather than a purely operational transportation decision. Developing alternative route plans, maintaining route-performance records, and establishing response protocols during flood events can improve transportation reliability and reduce disruption exposure. Second, inventory buffering should be applied selectively to products with high stockout costs or limited replenishment flexibility. Such an approach enables firms to balance service continuity with working-capital efficiency (Chopra & Sodhi, 2014).

The results also highlight the importance of information visibility. SMEs can strengthen resilience through relatively low-cost investments such as flood-warning applications, traffic-monitoring systems, and collaborative communication networks with suppliers and logistics providers. Improved access to timely information enhances routing flexibility and supports more effective adaptation decisions (Pettit et al., 2019).

From a policy perspective, investments in transportation reliability and localized flood-information systems may generate significant resilience benefits for SMEs. In addition to physical infrastructure improvements, public agencies should prioritise real-time road-status platforms and flood-monitoring systems that improve operational visibility and reduce disruption uncertainty. Targeted financial assistance and resilience-support programmes may also help SMEs manage the working-capital pressures associated with recurring environmental disruptions (UNDRR, 2023; OECD, 2023).

Several limitations should be acknowledged. Route classifications may not fully capture the complexity of transportation decisions, particularly when firms utilise multiple routes simultaneously. In addition, unobserved operational shocks such as supplier disruptions and fuel-price fluctuations may influence adaptation behaviour despite the use of fixed-effects estimation. Future research should examine adaptation behaviour across different geographical contexts and incorporate higher-resolution transportation and environmental data. Further investigation into the roles of digital technologies, insurance mechanisms, and financial constraints would also contribute to a deeper understanding of resilience strategies under recurring climate-related disruptions.

6. Conclusion

This study examined how SMEs operating in flood-prone environments adapt their logistics operations under recurring flood exposure. Focusing on SMEs in Terengganu, the research investigated the relationship between flood risk, route choice, and inventory buffering, while accounting for the interdependence between flexibility-based and redundancy-based adaptation mechanisms. Using a structural panel-data framework, the study addressed an important gap in the logistics resilience literature by modelling route adaptation and inventory buffering as jointly determined decisions rather than independent responses.

The findings reveal that flood exposure significantly increases the likelihood of avoidance routing among SMEs, indicating that route choice functions as a deliberate risk-management strategy under recurring environmental uncertainty. The results also show that higher flood exposure is associated with greater inventory buffering in conventional models. However, once route-choice endogeneity is addressed, the direct impact of flood exposure on inventory buffers becomes substantially weaker. The structural estimates demonstrate that avoidance routing reduces reliance on inventory redundancy, providing evidence of a substitution mechanism between logistics flexibility and inventory buffering.

The study contributes to theory in three important ways. First, it extends climate-related logistics research by conceptualising flood risk as a recurring operational condition rather than a rare disruption event. Second, it highlights the importance of reliability risk as a critical driver of logistics adaptation behaviour. Third, it demonstrates that resilience among SMEs is achieved through a constrained optimisation process in which firms allocate limited resources between avoidance and absorption strategies.

From a practical perspective, the findings suggest that improving route flexibility, transportation visibility, and access to real-time information can enhance resilience while reducing dependence on costly inventory buffers. For policymakers, investments in transportation reliability, flood information systems, and SME resilience support programmes may strengthen regional supply chain performance and reduce the economic consequences of recurring climate-related disruptions.

Overall, the study demonstrates that SME resilience under flood risk is not determined by a single adaptation mechanism but by the strategic balance between flexibility and redundancy. Understanding this balance is increasingly important as climate-related disruptions become a persistent feature of modern supply chains.

Data Availability Statement

The data for this study are available from the corresponding author upon reasonable request.

Conflict of Interest

The authors declare that there are no conflicts of interest associated with the publication of this article.

Author Contributions

Mohamad Shukri Johari: Conceptualization, project administration, investigation and writing - original draft preparation.
Irwan Ibrahim: Methodology, conceptualization and writing review and editing.
Norina Ahmad Jamil: Investigation, formal analysis and writing - review and editing.
Hairin Nisa Meor Nordin: Data curation and formal analysis.
Azilah Anis: Investigation and validation.
Mohd Hafiz Zulfakar: Data curation and resources.
Nur Rahmas Mohd Saman: Data curation and resources.
Mohd Ariff Kamaludin: Supervision, methodology, formal analysis, writing - review and editing and correspondence.

All authors have read and approved the final version of the manuscript and agree to be accountable for all aspects of the work, ensuring the accuracy and integrity of the research.

Disclosure of AI Use

This manuscript was prepared with the assistance of ChatGPT (OpenAI) for language refinement, structural organization, and editorial improvement of the manuscript text. The tool was used solely to support clarity and coherence in the presentation of the research. All academic arguments, research design, methodological framework, data analysis procedures, and interpretation of findings were developed and validated by the authors. The authors critically reviewed and verified all outputs generated during the writing process and assume full responsibility for the accuracy, integrity and conclusions presented in this publication.

Ethics Statement

This research was conducted in accordance with accepted academic research ethics standards. The study involved voluntary participation from small and medium-sized enterprises (SMEs) in Terengganu who provided operational insights related to logistics practices and flood-related disruptions. All participants were informed about the purpose of the study and their participation was based on informed consent.

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