Physical Flood Vulnerability of Residential Properties in Coastal, Eastern England

Extended Summary

(This document presents the principal results of the entire PhD dissertation. Samples of intermediary results are also provided, but not explanations of, nor background to, nor justifications for, the methods and results. For such information, the entire dissertation should be read.)

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Symbols Used in This Extended Summary

avg	average
A	residence plan area (approximate floor area of one storey) [m^2]
DS	level of the damage scale $\in$ {0, 1, 2, 3, 4, 5} and reported as DS0, DS1, DS2, DS3, DS4, or DS5.
f	flood depth [m]
f_{diff}	flood depth differential between the inside and outside of a residence [m]
FIR	Flood Infiltration Rate [m^3 s^{-1}]
FRR	Flood Rise Rate [m s^{-1}]
HGISL	Halifax General Insurance Services Ltd.
j	number of storeys or levels in a residence [no units]
LEP	loss equivalent percentage [no units]
max	maximum
min	minimum
ΔP	pressure difference [Pa]
v	velocity [m s^{-1}]
Π	external residence perimeter [m]

1. Coastal Settlements at Risk

The work presented in this dissertation is described, previewed, and placed in the context of past flood disasters and increasing flood vulnerability in coastal, eastern England. This dissertation was part of the project "Coastal Settlements at Risk" funded by Halifax General Insurance Services Ltd. (HGISL) (Kelman *et al.*, 2002; Thomalla *et al.*, 2002). This project ran from 1999-2002 examining flood risk in coastal, eastern England with the aim of making a significant contribution to the understanding of flood risk to the built environment, especially residential properties. The work of Brown (2003) was also part of this project. Brown (2003) researched, set up, and ran hydrodynamic models to simulate flooding from a storm surge in the case study site of Canvey Island (see Chapter 4).

The overall objective of this dissertation on the physical flood vulnerability of residential properties is to demonstrate that significant improvements could and should be made in the manner in which society manages natural disaster risk. More specifically, the subobjectives are:

- To demonstrate this objective for the particular case of flood damage to residences in coastal, eastern England.
- To better describe, quantitatively and qualitatively, the risks for this case.

In order to meet these objectives, this dissertation illustrates for coastal, eastern England:

- The significance of flood depth differential (f_{diff}) and flood velocity (v) in causing flood damage to residences.
- The importance of structural failure in residences for overall flood damage.
- The improvement of the profiling of physical vulnerability for residences at risk from flooding.
- The usefulness of first-order calculations with respect to the first two points, i.e. residence structural failure during floods, to achieve the third point, i.e. improved vulnerability profiling.

To describe flood effects on buildings, a damage scale was developed for floods (Table 1). Each damage scale (DS) level represents a threshold in which the hazard event affects the residence in a fundamentally different, and more damaging, manner.

Table 1: Damage Scale for Floods

Damage Scale (DS) Level	Water Interaction with Structure
DS0	No water contact with structure.
DS1	Water contacts outside of structure but does not enter.
DS2	Water infiltrates (i.e. seeps or leaks in through small apertures). OR External features are damaged or removed by water or debris.
DS3	Water or debris penetrates through a closed or covered opening (probably by breaking the opening); for example, a window or a door.
DS4	Water or debris penetrates through a route not including an opening (structural integrity is attacked); for example, a wall or roof.
DS5	Structure is damaged beyond repair; for example, walls collapse, the structure moves, or the foundation is undermined.

Despite some rare examples of ambiguities, Table 1 provides a clear framework for assessing flood damage to residences. This table was used as the basis for vulnerability and risk assessments.

2. Risk Environment for Residences in Coastal, Eastern England

The development of a method for quantitatively describing the risk for residences subjected to floods in coastal, eastern England is described. A literature review establishes that risk is a combination of hazard and vulnerability and may be interpreted as a loss function. Flood hazards for coastal, eastern England are described followed by residence vulnerabilities for coastal, eastern England.

The most detailed U.K. studies on damage and loss for residences in floods have considered almost exclusively depth-damage curves. Flood depth is assumed to rise slowly so that damage occurs only due to water touching the damaged item or structure and not due to any physical force, pressure, or energy imparted to an item, component, or structure. DS1 and DS2 in Table 1 are explored without considering the higher DS levels. In contrast, many non-U.K. studies indicate the importance of flood characteristics other than depth, including velocity, depth differential, waves, sediment, contaminants, and flood duration. Another weakness in the literature, particularly in the U.K., is that an explanation of the physical mechanisms by which floods damage residences is rarely provided.

This dissertation makes an original contribution to research by tackling these knowledge gaps. In order to tackle the identified gaps, the risk equation chosen is:

$$\text{risk} = \sum_{\text{All residences}} \int_{\text{All values of the hazard parameter}} \begin{array}{r} [\ (\text{hazard parameter value exceedance probability}) \\ \times (\text{vulnerability to that hazard parameter value})\ ] \\ \text{integrated with respect to the hazard parameter.} \end{array}$$

The hazard exceedance probability is for flood hazard parameters other than slow-rise depth. Vulnerability examines the mechanisms of residence damage, predicts which damage would occur for which residences, and estimates the proportion of the total value of each residence lost in a given hazard scenario. In theory, the risk would measure the expected proportion of the total value of residences in a community expected to be lost over a given timeframe.

The risk environment examined in this dissertation for residences in coastal, eastern England is plugging, at the first order, the knowledge gap in damage from floods other than due to slow-rise depth. This first order approach assists in identifying and detailing the main hazard parameters and the main damage modes to explore.

3. Flood Actions on Residences

Analyses of flood damage to residences in the U.K. traditionally focuses on damage from slow-rise flood depth. This study's mandate is to investigate flood characteristics not previously examined in detail in order to contribute new knowledge and techniques.

Such characteristics include forces, pressures, chemical reactions, and other impacts which a flood could impose on a residence. Collectively, they are termed "actions" for this study and refer to something to which a structure responds. Flood actions describe acts which a flood could do to a residence, potentially causing damage.

The typology developed for flood actions on residences is:

1. Hydrostatic actions (actions resulting from the water's presence):
    - Lateral pressure from depth differential (f_{diff}).
    - Capillary rise.
2. Hydrodynamic actions (actions resulting from the water's motion):
    - Velocity: moving water flowing around a residence imparting a hydrodynamic pressure.
    - Velocity's localised effects, such as at corners.
    - Velocity: turbulence.
    - Waves changing hydrostatic pressure.
    - Waves breaking.
3. Erosion Actions (water moving soil; the water's boundary becomes dynamic and moves into the adjacent solids).
4. Buoyancy action: the buoyancy force.
5. Debris actions (actions from solids in the water):
    - Static actions.
    - Dynamic actions.
    - Erosion actions.
6. Non-physical actions.
    - Chemical actions including contact from slow-rise flood depth (f).
    - Nuclear actions.
    - Biological actions.

Interactions and combinations must also be considered.

The flood actions on residences which are most relevant and most applicable to analysis for loss prediction are the combination:

- Lateral hydrostatic pressure (ΔP) imparted by instantaneous f_{diff}.
- Lateral hydrodynamic pressure (ΔP) imparted by instantaneous v.
- Damage from water contact due to f.

Focusing on these three actions produces a first-order analysis of the physical vulnerability of residences to floods.

The uncertainties in this analysis, introduced by not directly considering other actions including waves and debris, may be reduced once more data and experience are available. Meanwhile, a significant contribution to knowledge and a clear advancement of flood damage prediction and analysis are attained by considering in detail the flood actions of f, f_{diff} and v.

4. Case Study Sites

Coastal, eastern England from the Thames Estuary to the Humber Estuary is this study's area of interest (Figure 1). Two case study sites could realistically be examined. The criteria considered are:

- Natural environment:
  - Coastal situation.
  - Hydrodynamic characteristics
  - Topographic characteristics.
- Built environment:
  - Nature and state of sea and flood defences.
  - Flood vulnerability characteristics of residences.
- Other:
  - Flood disaster history.
  - Flood disaster potential.
  - Interest of different stakeholders, including the insurance industry, in flooding at the site.
  - Potential for flood actions of interest to manifest, particularly from storm surge.

Following research and field visits, Kingston-upon-Hull and Canvey Island were selected as case study sites (Figure 1). They provide complex, coastal, urban areas which are vulnerable to flooding, particularly the flood actions of ΔP from f_{diff} and v (Table 2).

Figure 1: England and Wales and the Case Study Sites
(Reproduced from the 1999 Ordnance Survey map with the permission of the Controller of Her Majesty's Stationery Office, © Crown Copyright NC/01/26576.)

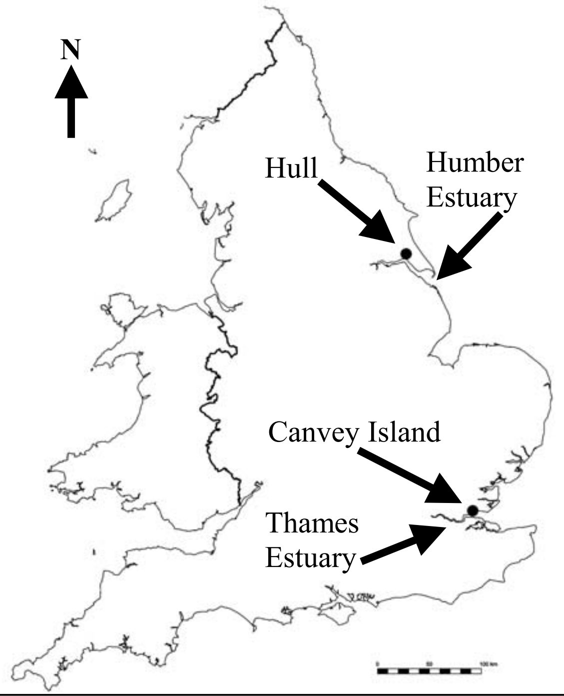


Table 2: Summary of Characteristics of Canvey Island and Hull

Criterion	Canvey Island	Hull
Coastal situation.	An island sited in the mouth of an estuary.	Sited where a river meets an estuary.
Hydrodynamic characteristics.	Estuary has a large catchment, a large tidal range, strong currents, and a large sediment load.	Estuary has a large catchment, a large tidal range, strong currents, and a large sediment load.
Topographic characteristics.	Flat, lying below the mean high water mark. Sand flats lie between Canvey Island and the open sea.	Flat, with much area lying below the highest recorded tide. A storm surge must propagate up the Estuary around some curves.
Sea and flood defences.	Surrounded by substantial structural defences but the defences have weaknesses.	A variety of defences, some concrete, some shingle. A barrage sits at the mouth of the River Hull to prevent a storm surge from the Humber Estuary propagating upstream.
Flood disaster history.	Prior to modern settlement, frequent sea flooding. Devastated by the 1953 storm surge.	Frequent flooding and significant storm surge events during the past century.
Flood disaster potential.	High from storm surge. Heavy rainfall could also overwhelm the drainage system or overflow from areas of standing water.	High from storm surge, river flooding, or conjunctive events.
Residences in relation to principal hazard parameters.	Residences lie below the mean high water mark. The sea defences are walls, hence breaching, overtopping, and undermining are possibilities. f_{diff}, v, and waves could impact on residences. Water could come from any direction.	Residences lie above the mean high water mark. The sea defences form the shoreline, so breaching is not possible but overtopping and undermining could occur. v and waves would be the main impacts on residences. Significant f_{diff} could occur, but would be unlikely. A conjunctive event with river flooding implies that water could come from any direction.
Residence physical vulnerability.	Vulnerable to flood actions across Canvey Island. Strong potential for secondary hazards following a flood event.	Three new communities built adjacent to the estuary which have not yet experienced a major flood event. Strong potential for secondary hazards following a flood event.

5. Residence Survey Method

The purpose of surveying residences in the case study sites is to identify the features of residences which are most physically vulnerable to the flood actions of ΔP from f_{diff} and v. To establish this first-order level of vulnerability, potential routes of flood water infiltration into the structure and potential mechanisms of damage and failure must be identified. The method must also be doable and repeatable without excessive resource expenditure. To meet these criteria, the residence survey examined only external features identifiable from public land.

Not all residence characteristics impact the physical vulnerability to floods. The data collected achieved a balance between (a) obtaining all data needed without repeating surveys in each location and (b) ensuring that the data are collectable, analysable, and relevant. An analogous trade-off was between the number of residences surveyed and the amount of data per residence.

Two levels of surveying were completed. The first level was a quick survey for over 1,000 residences in each case study site to record the main defining qualities of residence vulnerability to ΔP from f_{diff} and v. Preliminary analysis concluded that these defining qualities are those listed in Table 3. This rapid house-by-house census was completed in representative areas throughout each case study site to be indicative of the residential building stock.

Table 3: Template for Defining Residence Classes

	Max. # of storeys →	1	2	3	4
Configuration for Houses	houses, 1 exterior wall				
	houses, 2 adjacent exterior walls				
	houses, 2 opposite exterior walls				
	houses, 3 exterior walls				
	houses, 4 exterior walls				
	houses, other configuration				
	Level (and total # levels) →	ground	1st floor	2nd floor	3rd floor
Configuration for Flats	flats, 1 exterior wall				
	flats, 2 adjacent exterior walls				
	flats, 2 opposite exterior walls				
	flats, 3 exterior walls				
	flats, 4 exterior walls				
	flats, other configuration				
caravans/mobiles (all are expected to be 1 storey with 4 exterior walls but any variation would be recorded)					

The second level was a photographic survey of several hundred residences in each case study site. This survey involved taking photographs of all visible walls of a residence and using the photographs to extract relevant vulnerability characteristics. A representative sample of each case study site was covered by including in the photographic survey the same proportion of residences from each class as were observed during the quick survey. In addition to the data in Table 3, the data collected from the photographs included:

- Presence or absence of basements and lofts.
- Number of garages.
- Relative height of residence (height above sea level).
- Distance from the ground to the ground floor bottom.
- Wall height.
- Exterior perimeter (Π).

- Plan Area (A).
- Design purpose.
- Age.
- Walls: Materials, condition, and geometry.
- Doors: Materials, condition, and geometry.
- Windows: Materials, condition, and geometry.
- Other Openings: Materials, condition, and geometry.

6. Residence Survey Results

The data collected are presented for each case study site. One useful result for later chapters is that the height of the ground floor above ground level is usually approximately 0.3 m.

Analysis indicated that neither exterior wall configuration nor the number of storeys or levels (j) correlates well with either residence plan area (A) or external residence perimeter (Π). Furthermore, houses and flats are similar enough that they do not need to be considered separate categories. The proposed choice of exterior wall configuration and j to define residences (Table 3) is thus inadequate.

Instead, the three variables A, Π, and j better define the first-order, physical vulnerability of residences to ΔP from f_{diff} and v.

The residences in the two case study sites are remarkably similar, particularly for A, Π, and j. Thus, taking the combination of Canvey Island and Hull is reasonable for identifying a typical residence by A, Π, and j for this study. The similarities emerge because most of the residences examined were modern, i.e. built after 1960. Combining the data sets from both case study sites implies that the work here is effectively for typical, modern residences in eastern England rather than exclusively for the two case study sites.

The modern age of the observed residences simplifies the vulnerability analyses. Only cavity walls and double-glazed door and window units need to be considered. A disadvantage is that it is unlikely that many of the residences surveyed have experienced floods, so immediate validation of results is challenging. Nonetheless, the analyses are important for estimating potential, future flood consequences. The focus on modern residences, however, yields results limited in their applicability to only the observed residence types.

From the combined data, eight A-Π pairs were determined to be realistic and existing (Table 4). Each of these eight pairs was matched with the observations of $j \in \{1,2,3,4\}$ to yield 32 different residence types.

Table 4: Realistic A-Π Pairs for Coastal, Eastern England

Π (m)	A (m^2)	General Configuration Description
12	38	small residence with 1, 2, 3, or 4 exterior walls
12	55	medium residence with 1 or 2 exterior walls
12	84	large residence with 1 or 2 exterior walls
25	38	small residence with 3 or 4 exterior walls
25	55	medium residence with 2, 3, or 4 exterior walls
25	84	large residence with 2, 3 or 4 exterior walls
41	55	medium residence with 3 or 4 exterior walls
41	84	large residence with 3 or 4 exterior walls

7. Flood Failure Flowchart Prelude

The consequences of potential flood actions on the residences which were surveyed is now examined in order to determine how damage to residence components may occur. The aim is to predict the components which would be most likely to fail under given f_{diff}-v scenarios and to produce a flowchart indicating likely failure pathways.

Only residence components observed in the case study sites are examined: windows (glass and non-glass components), walls, doors (glass and non-glass components), floors, foundations, and roofs. Basements, for example, are not considered because none were observed. Table 5 summarises the results from this initial investigation.

Table 5: Summary of Initial Analysis of Failure Modes

Failure Mode	Detailed Analysis Required?
Flood infiltration.	Yes. See Chapter 8.
Window glass.	Yes. See Chapter 10.
Window locks/catches or hinges.	Unclear. Clarified in Chapter 11.
Window mullions, transoms, frames, or joints.	Unlikely. Clarified in Chapter 11.
Window attachment mechanisms.	Unlikely. Clarified in Chapter 11.
Walls.	Yes. See Chapter 9.
Doors.	Unclear. Clarified in Chapter 11.
Floors.	No.
Foundations.	No.
Roofs.	Unclear. Clarified in Chapter 11.

8. Flood Rise Rate Inside a Residence

Flood scenarios for all possible rates of water rise outside a residence, from negligible to nearly instantaneous, can be envisioned. ΔP from f_{diff} and v would force water into the residence through any cracks or openings. The water would then rise inside the residence reducing f_{diff} and consequently ΔP. Knowing the rate at which water infiltrates from outside to inside a residence under different scenarios as well as the rate of water rise inside a residence is thus necessary for determining the range of possible ΔP which could be imposed on residences. The flood infiltration rate is termed FIR in m^3/s and the flood rise rate inside a residence is termed FRR in m/s (presented here in mm/s). FRR = FIR / A.

Past studies on the rate of water infiltration into buildings were not found. Instead, infiltration studies of air are adapted for applicability to water infiltration. These studies emerge mainly from the literature on natural ventilation and air leakage rates. They focus on air flow under external wind pressure through small openings termed cracks. Examples of cracks are the space between a window frame and the wall, the gap underneath a door, and pores in brickwork and render.

Using the power law, rather than the quadratic formula, crack flow theory for air was adapted for water. Integrating flow rate with respect to height along vertical cracks was necessary to account for the change with height of ΔP due to f_{diff}. As well, the calculations assumed that f_{diff} is reached instantaneously and the calculations were completed for only the instant at which f_{diff} is attained, i.e. effectively the point in time at which the flood contacts the residence. Thus, assuming that neither the flood level nor v changes, the FRR values reported are the maximum feasible in each situation because as soon as the flood contacts the residence, infiltration occurs and f_{diff}, and hence ΔP and FRR, decrease.

Table 6 indicates the order of magnitude of FRR_{max} for single residence components for a typical range of f_{diff} and v with $A \in \{38 \text{ m}^2, 55 \text{ m}^2, 84 \text{ m}^2\}$ as determined in Chapter 6.

Table 6: Order of Magnitude of FRR_{max} (m/s) For Single Components

Component	Order of Magnitude of FRR_{max} (mm/s) considering $f_{diff} \leq 2.5$ m (one storey) and $v \leq 5.0$ m/s
door, hinged, non-weather-stripped (including frame)	0.1
door, sliding, non-weather-stripped (including frame)	0.1
door, hinged, weather-stripped (including frame)	0.1
door, sliding, weather-stripped (including frame)	0.01
floor, suspended timber	1
opening, discharge pipe (including joint)	0.01
opening, discharge pipe, joint only	0.01
opening, pipe (including joint)	0.01
opening, pipe, joint only	0.01
opening, postal flap (including joint)	1
opening, postal flap, joint only	0.01
opening, sealed spiral duct (including joint)	1
opening, sealed spiral duct, joint only	0.01
opening, vent (including joint)	1
opening, vent, joint only	0.1
wall perimeter, rendered	0.1
wall perimeter, unrendered	0.1
wall and floor/ceiling interfaces (timber ground floor)	1
wall and floor/ceiling interfaces (concrete ground floor)	0.1
window, hinged, non-weather-stripped (including frame)	0.1
window, sliding, non-weather-stripped (including frame)	0.1
window, hinged, weather-stripped (including frame)	0.01
window, sliding, weather-stripped (including frame)	0.01

The order for residence components from least to most contribution to FRR per component is:

1. pipe
   window, weather-stripped
2. concrete floor interface with wall perimeter
   door
   window, non-weather-stripped
   wall perimeter
3. duct
   postal flap
   vent
4. suspended timber floor (including interface with wall perimeter)

The numbers and properties of components affect their ultimate influence on overall FRR:

- Vents and ducts tend to appear high up.
- Residences tend to have more windows than doors and tend to have few other openings.
- Residences tend to have only one postal flap.

Therefore, the component which contributes most to FRR is the presence of a suspended timber floor followed by the presence of a postal flap. Walls, windows, and doors would be approximately equivalent. Vents and ducts would contribute significantly to FRR for floods inundating the entire ground floor or for residences which have these components low down.

In order to establish an upper bound for FRR, Table 7 provides FRR for a typical residence designed to be leaky. Table 7 yields FRR < 20 mm/s and this limit is reached for deep floods only. The suggested typical value is FRR ≈ 5 mm/s. The upper bound and typical value apply to any residence in the case study sites.

Table 7: Flood Rise Rate Inside a Typical but Leaky Residence

		f_{diff} (m)					
		0.0	0.5	1.0	1.5	2.0	2.5
v (m/s)	0.0	0 mm/s	1 mm/s	2 mm/s	4 mm/s	7 mm/s	11 mm/s
	0.5	0 mm/s	1 mm/s	2 mm/s	4 mm/s	7 mm/s	11 mm/s
	1.0	0 mm/s	1 mm/s	2 mm/s	4 mm/s	7 mm/s	11 mm/s
	1.5	0 mm/s	1 mm/s	2 mm/s	4 mm/s	8 mm/s	11 mm/s
	2.0	0 mm/s	1 mm/s	3 mm/s	5 mm/s	8 mm/s	12 mm/s
	2.5	0 mm/s	1 mm/s	3 mm/s	5 mm/s	9 mm/s	13 mm/s
	3.0	0 mm/s	2 mm/s	3 mm/s	5 mm/s	10 mm/s	13 mm/s
	3.5	0 mm/s	2 mm/s	3 mm/s	6 mm/s	11 mm/s	14 mm/s
	4.0	0 mm/s	2 mm/s	4 mm/s	6 mm/s	12 mm/s	15 mm/s
	4.5	0 mm/s	3 mm/s	4 mm/s	7 mm/s	12 mm/s	16 mm/s
	5.0	0 mm/s	3 mm/s	5 mm/s	7 mm/s	13 mm/s	17 mm/s

Table 7 illustrates that even if f_{diff} were low at 0.5 m, the minimum $f_{diff} > 0$ considered, ΔP due to f_{diff} would have at least several seconds over which to act to potentially break glass or walls before enough water would be inside the residence to counteract the external ΔP. The FRR calculation thus demonstrates that, under the assumption that f_{diff} and v are reached instantaneously, ΔP due to f_{diff} must be considered. Infiltration does not occur quickly enough to negate this external ΔP. The analysis of ΔP breaking other residence components should proceed.

For influencing FRR, rendering walls makes little difference but sealing windows and doors and caulking their frames can have a minor impact. The presence or absence of suspended timber floors and postal flaps has the most impact. The rare case of a large opening such as a vent or duct low down could double FRR. Sealing such an opening, although not necessarily sealing the joint, would significantly reduce FRR.

These calculations and results indicate how infiltration might be influenced but do not suggest that the goal is to reduce or to prevent infiltration. This issue is discussed in Chapter 13.

Validation of these results could only be completed with anecdotes from people who have experienced the infiltration of flood water into their residence. These anecdotes generally corroborate the results here, but definite statements are not possible because quantitative estimates of FIR, FRR, f_{diff}, and v are not given in the anecdotes. As well, concerns with the calculations—e.g. assuming that crack geometry does not vary around a component's perimeter—and concerns with the model—e.g. assuming uncontaminated flood water and neglecting flood water entry through toilets and sinks—indicate the limitations of these calculations.

Nonetheless, the FRR analysis has validated the study of damage from f_{diff} and v due to ΔP. The FRR calculation also suggests that sealing a residence to flood water will not necessarily minimise overall damage if other components are broken by a large ΔP.

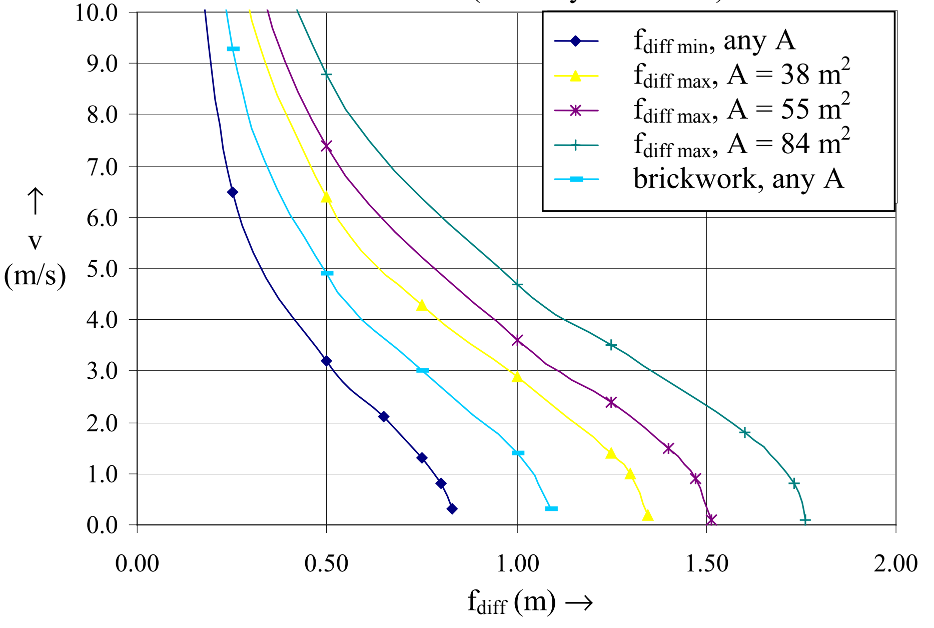
9. Wall Failure

Wall collapse due to a combined lateral load of hydrostatic and hydrodynamic flood water pressure was examined. Cavity walls represent more than 95% of external residence walls in the case study sites, hence only these walls are considered. These walls comprise a brickwork outer leaf attached to a blockwork inner leaf by metal ties and are neither precompressed, nor prestressed, nor reinforced. The failure analysis does not consider an entire external wall. External walls on residences are partitioned vertically by supported timber floors and horizontally by inner, partition walls. This section of a wall is termed a wall panel and is the residence component used for the failure analysis.

A literature review, empirical evidence, and a theoretical analysis of the mechanism of failure of a cavity wall under lateral pressure suggest that, despite the ties, the two leaves of a cavity wall act as separate leaves in failure. For large pressures, the ties appear to transfer minimal load. As well, a modified form of yield line analysis was deemed to be the best analytical method, although a theoretical explanation of the failure mechanism, different to that for concrete, was required for brickwork and blockwork failure. The literature review indicated that wall panels in the case study sites under the flood's linear loading would be expected to fail when the linear load's ΔP_{avg} approximately equals 1-10 kPa, with the lower end of this range more common than the upper end.

The calculations yielded graphs in the form of Figure 2. For most f_{diff}-v combinations, the range of ΔP_{avg} under which panels start to fail runs from just over 1 kPa to approximately 40 kPa with the most common being between just over 1 kPa and 10 kPa. Some weak panels have 0.5 kPa < ΔP_{avg} < 1.0 kPa for certain f_{diff}-v combinations.

Figure 2: Sample f_{diff}-v Failure Curves from Wall Failure Calculations (2-Storey Residence)



This range for ΔP_{avg} conforms to the range predicted with the literature review, somewhat validating the method and assumptions chosen. One outcome from these calculations is that defining a specific ΔP_{avg} for a panel's failure is not possible as with uniform loading. The combination of hydrostatic and hydrodynamic pressures means that ΔP_{min} for failure shifts according to the f_{diff}-v combination. Either f_{diff} or v must be defined before ΔP_{min} for failure may be calculated.

For $v = 0$ m/s, wall panels start failing at approximately $f_{diff} = 0.8$ m plus the height of the ground floor above ground level. Most wall panels would have failed by $f_{diff} = 2.0$ m plus the height of the ground floor above ground level. This 1.2 m range is relatively narrow, indicating a fairly rapid jump across a threshold from non-structural failure, such as glass breaking or infiltration, to structural failure. With $v > 0.0$ m/s, for some wall panels, f_{diff} for collapse can drop below 0.5 m plus the height of the ground floor above ground level. If a residence were completely sealed and $f_{diff} \approx 1.0$ m, the swell from non-breaking waves or from boats or vehicles travelling through the water could raise f_{diff} over the threshold and precipitate structural failure.

This Chapter discusses the most effective means of strengthening a wall panel and the limitations of the calculations. More detail than this extended summary provides is required to discuss the issues.

Much research into unreinforced masonry collapse under lateral pressures has yet to be completed and caution is suggested in interpreting some of the results presented. Despite the assumptions made and the uncertainties, the method used is validated by comparison with the literature and it produces results based on a plausible failure mechanism. The goal of obtaining first-order results was achieved and uncertainties were analysed.

10. Glass Failure

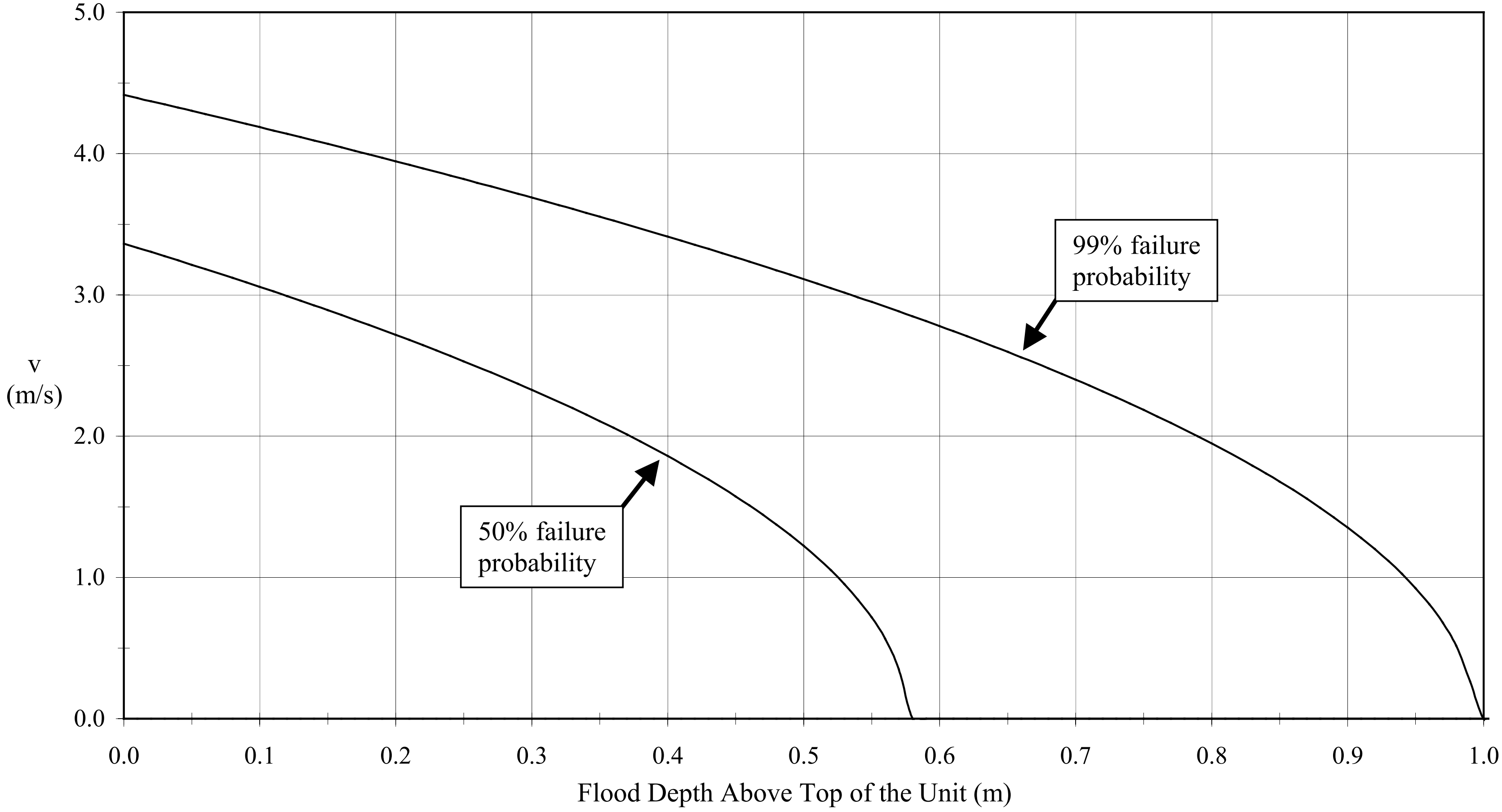
In the case study sites, normal-strength, soda-lime, 4-mm-thick glass in double-glazed window and door units was most common. This type of unit is used for the analysis here.

A literature review established the appropriate theory as thin plates undergoing large deflections and probabilistic failure according to the Weibull distribution. The specific interpretation of the Weibull distribution depends on the specific needs of each problem and an interpretation relevant to this study is developed.

Empirical evidence from the literature review was available for only uniform loads on mainly single-glazed units. Failure ΔP is generally between 1 kPa and 10 kPa although most tests use pane areas greater than 1 m^2. Smaller panes generally have failure $\Delta P > 10$ kPa. Translating the uniform load results into a hydrostatic plus hydrodynamic ΔP is not straightforward, but a rough estimate would be that failure would occur when the linear load's ΔP_{avg} approximately equals the uniform failure ΔP.

Aalami and Williams (1975) provide computer-synthesised data which were used for calculating the probabilities of failure under various f_{diff}-v combinations. The calculations yielded graphs in the form of Figure 3. ΔP for a probability of failure of 50% for the largest double-glazed units observed in the case study sites (those on doors) is in the range 10-20 kPa. The range for smaller double-glazed units is 20 kPa to 138 kPa for ΔP for a probability of failure of 50%. These values are almost exactly double the failure ΔP reported in the literature for comparably-sized single-glazed units which somewhat validates the method and assumptions chosen. More detail than this extended summary provides is required to fully discuss this issue.

Figure 3: Sample f_{diff}-v Failure Curves from Glass Failure (for a Unit 1.00 m × 1.00 m × 4+4 mm thick)



Further analysis indicated that the glass units important for the vulnerability analysis conducted for this study are large units on doors, such as the unit analysed in Figure 3. With $v = 0.0$ m/s, these units have a non-negligible probability of failing when the flood water is part way up the pane and a high probability of failing when the pane is nearly inundated which means approximately $f_{diff} \geq 1.5$ m plus the height of the ground floor above ground level. Window units are too high and too small to be of concern for this study.

The area of the unit or pane is a significant factor in determining unit strength. As this area increases, strength decreases. Glass thickness also has a strong influence on unit strength. A 2 mm increase in the thickness of each pane more than doubles the strength of most double-glazed units.

The main limitations of this analysis are the interpolations and extrapolations required due to a lack of available data and the influence of in-service exposure conditions on glass strength. Despite these issues, the results presented here match well with literature results.

Much research into glass failure has yet to be completed and caution is suggested in interpreting some of the results presented. Irrespective, the method used is validated by comparison with the literature and produces credible results. The reason is that the goal was to obtain only first-order results. Approximations were made, the calculations were completed, and the results were reported in a manner that all uncertainties were encompassed.

An adequate understanding and prediction of glass failure has been achieved for the units in residences which are most vulnerable to ΔP from f_{diff} and v. Nonetheless, reasons unrelated to flood actions must be considered for formulating policy on strengthening glass in residences.

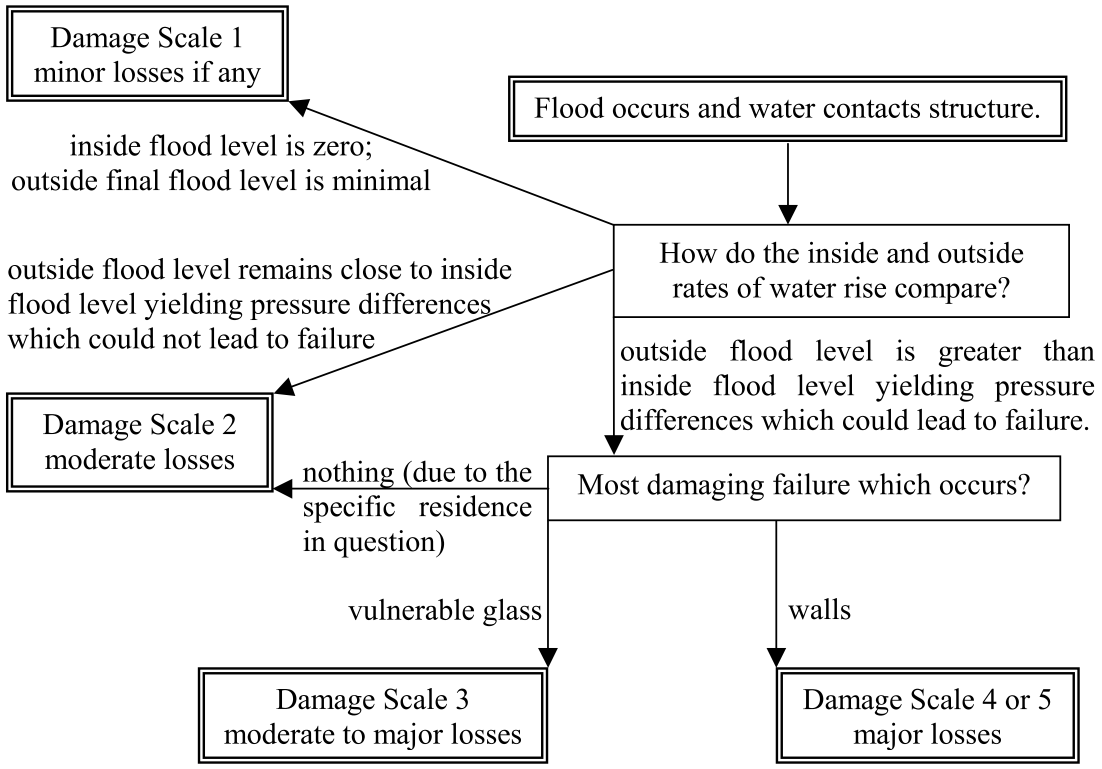
11. Flood Failure Flowchart

Chapter 8 indicated that water rises slowly enough inside residences that significant ΔP from f_{diff} would be imposed on a residence in the case of a fast-rise flood. Chapters 9 and 10 illustrate that failure in, respectively, cavity walls and glass with large area and low height above ground would be expected sometimes at $f_{diff} \approx 1.0$ m and in most circumstances for $f_{diff} \geq 1.5$ m plus the height of the ground floor above ground level.

Ambiguities in residence component failure present in Chapter 7 (Table 5) may now be reconsidered. Further examination of these components—roofs and non-glass components in doors and windows—indicated that their failure does not need to be further considered for a first-order analysis of residences in the case study sites subjected to ΔP from f_{diff} and v in floods.

The flowchart in Figure 4 illustrates the main failure pathways for a first-order analysis of residences in the case study sites subjected to ΔP from f_{diff} and v in floods. This schematic and the pathways represented are used to develop the vulnerability matrices (Chapter 12).

Figure 4: Flood Failure Flowchart



The principal limitations in the flood failure flowchart are that uncertainties remain due to lack of information and weaknesses in the analysis. Surprisingly few appropriate studies exist on the topics investigated for the flood failure flowchart. Thus, prior recommendations on flood damage reduction did not necessarily have a strong basis and, given the assumptions made, caution is also warranted in interpreting the results presented here.

Nonetheless, this study tackles the potential failure modes believed to be most significant for most observed residences to a level as best as feasible with the information currently available. The flood failure flowchart provides initial, first-order insight into the main failure modes which should be, and which have been, quantified in detail. Future studies would be appropriate for filling in gaps.

12. Vulnerability Matrices

The flood failure flowchart established that door glass breaking and walls collapsing were liable to be the main impacts of the flood actions of ΔP from f_{diff} and v on residences in the case study sites. Additionally, the ΔP values likely to cause such failures were quantified. This information now requires collation with Table 1, the damage scale for floods.

Chapter 6 illustrated that residences could be classified through the two dimensions of eight A-Π pairs and $j \in \{1,2,3,4\}$ yielding 32 different residence categories. In collating the work done so far, further analysis deemed Π to be of secondary importance to A and j. Therefore, only the twelve A-j combinations need to be considered.

Based on the results in this dissertation, twelve vulnerability matrices, one for each A-j residence class, were produced. A sample vulnerability profile for a typical residence in the case study sites is provided in Table 8.

Table 8: Sample Vulnerability Profile for a Typical Residence (A = 55 m^2 and j = 2)

Maximum Flood Velocity	Maximum Flood Depth Differential				
	0.0 m	0.5 m	1.0 m	1.5 m	2.0 m +
0.0 m/s	DS0	DS2 Even if glass doors, DS3 unlikely	DS4	DS4	DS5
0.5 m/s	DS0	DS2 Even if glass doors, DS3 unlikely	DS4	DS5	DS5
1.0 m/s	DS0	DS2 Even if glass doors, DS3 unlikely	DS4	DS5	DS5
1.5 m/s	DS0	DS2 Even if glass doors, DS3 unlikely	DS4	DS5	DS5
2.0 m/s	DS0	DS2 Even if glass doors, DS3 unlikely	DS4	DS5	DS5
2.5 m/s	DS0	DS2 Even if glass doors, DS3 unlikely DS4 if weak wall panels	DS4	DS5	DS5
3.0 m/s	DS0	DS2 Even if glass doors, DS3 unlikely DS4 if weak wall panels	DS4	DS5	DS5
3.5 m/s	DS0	DS4	DS4	DS5	DS5
4.0 m/s	DS0	DS4	DS5	DS5	DS5
4.5 m/s	DS0	DS4	DS5	DS5	DS5
5.0 m/s	DS0	DS4	DS5	DS5	DS5
5.5 m/s	DS0	DS4	DS5	DS5	DS5
6.0 m/s	DS0	DS4	DS5	DS5	DS5
6.5 m/s	DS0	DS4	DS5	DS5	DS5
7.0 m/s	DS0	DS4	DS5	DS5	DS5
7.5 m/s +	DS0	DS5	DS5	DS5	DS5

Figure 5: Example of a Hull Residence for Table 8 (Front and Back)

These twelve vulnerability matrices provide a system for predicting the consequences for a residence of given vulnerability characteristics, A and j, being subjected to specific hazard parameters, f_{diff} and v. This system's form is vulnerability profiles as f_{diff}-v matrices. The system is resolved to 0.5 m for f_{diff} and 0.5 m/s for v. These relatively wide bands encompass many uncertainties described for each individual calculation which inputs into the creation of the vulnerability profiles.

One aspect yet to be factored in is the height above ground level of the ground floor. Thus, the vulnerability matrices are as generic as possible, but this factor must be considered before applying the matrices. As well, the vulnerability matrices apply to only residences similar to those observed in the case study sites—relatively modern residences in England constructed from unreinforced masonry—but the method described could be used to develop vulnerability matrices for other residence types.

13. Analysis and Application

The results presented in this dissertation may be further analysed and may be applied to formulating flood management recommendations. This Chapter explores different practical applications. The discussions are quantitative and qualitative and provide further original contributions to research, particularly geared at fulfilling the objectives outlined in Chapter 1.

13A. Quantifying Risk as Loss Equivalent Percentages (LEPs)

The Loss Equivalent Percentage (LEP) method is developed here for a specific situation as an example of applying the vulnerability matrices for quantitative risk analysis. The LEP method converts the DS levels from Table 1 into a percentage representing loss; for example, the percent market value of structure, contents, finishes, and systems lost by a residence in a flood disaster. Such figures assist in calculating an adequate estimate of economic loss at the level of individuals, communities, or the flood-affected area. This value is indicative of, rather than completely representing, the flood's impact on residential areas.

For this LEP definition, illustrative DS-to-LEP conversion values are estimated in Table 9 for a typical case study site residence and in Table 10 for a residence modified to have high internal flood resistance.

Table 9: Illustrative LEPs for a Typical Residence

DS	0	1	2	3	4	5
Illustrative LEP	0%	2%	50%	60%	80%	100%

Table 10: Illustrative LEPs for a Residence with High Internal Flood Resistance

DS	0	1	2	3	4	5
Illustrative LEP	0%	2%	10%	20%	70%	100%

These LEP values and the vulnerability matrices were combined with outputs from simulations of storm surge flooding on Canvey Island completed by Brown (2003). Forty different scenarios were run:

- Sea defence breaches were simulated separately in two different locations on Canvey Island.
- In each breach location, breach widths of 50 m and 200 m were investigated separately.
- For each of the four breach scenarios, fast-rise (instantaneous, $f_{diff} = f$) and slow-rise ($f_{diff} = 0$) floods were examined. The slow-rise flood results represent a lower bound for LEPs for a given breach scenario while the fast-rise flood results represent an upper bound for LEPs for a given breach scenario.

- For each of the eight flood scenarios, all residences were assumed to have:
  - (a) either normal internal flood resistance or high internal flood resistance; and
  - (b) either normal residence walls or unusually weak residence walls.

In addition to these 32 scenarios, a third sea defence breach scenario was examined for the 2 flood scenarios and 4 residence scenarios. This breach scenario involved altering Canvey Island in the computer model so that residences within 100 m of the breached sea wall were replaced with thick vegetation, thereby creating a residence-free flood buffer zone.

Sample results are in Table 11.

Table 11: LEPs for Normal Residence Walls

Scenario	Flood (Hazard)	Residences (Vulnerability)	LEP Index
50 m breach	fast-rise	normal internal flood resistance	12%
50 m breach	fast-rise	high internal flood resistance	5%
50 m breach	slow-rise	normal internal flood resistance	10%
50 m breach	slow-rise	high internal flood resistance	2%
200 m breach	fast-rise	normal internal flood resistance	47%
200 m breach	fast-rise	high internal flood resistance	28%
200 m breach	slow-rise	normal internal flood resistance	36%
200 m breach	slow-rise	high internal flood resistance	7%

The following trends were observed:

- For the scenarios considered, the wider breach resulted in LEPs approximately three to five times higher than the narrower breach.
- For the scenarios considered, weak wall panels resulted in no apparent difference to the LEPs compared with normal wall panels.
- For the scenarios considered, the trend from highest to lowest LEPs was:
  - -fast-rise flood, normal internal flood resistance
  - -slow-rise flood, normal internal flood resistance
  - -fast-rise flood, high internal flood resistance
  - -slow-rise flood, high internal flood resistance
- For the scenarios considered, the location of the breach changed the LEPs by 10%-50%.
- For the scenarios considered, the buffer zone with thick vegetation approximately halved the LEPs.

Many assumptions were necessary to reach the results, so caution is warranted in developing mitigation options from the scenarios presented here. Policies promoted and decisions made should always take into account the uncertainties and unknowns. Nonetheless, the quantification of risk through LEPs yields insights which assist in understanding and analysing flood risk to residences.

13B Analysis Strategies and Decision Making

This research also provides qualitative input into analysis strategies and decision-making processes regarding the management of flood damage to modern residences in coastal, eastern England. The focus is on strategies to use for analysis and the options available rather than recommending specific options for all circumstances. Lessons which could be learned from this dissertation are articulated and provide guidance for an individual's, community's, or sector's choice for managing flood damage to residences.

Issues of concern in using the results here for decision making are:

- The choice of analysis methods and theoretical failure mechanisms for wall failure (Chapter 9) and glass failure (Chapter 10) might not have been correct, leading to potentially erroneous results.
- Interaction amongst failure mechanisms has not been considered. For example, as one leaf of a cavity wall starts to fail, doors and windows could be subjected to extra stress resulting in them failing. Similarly, ΔP leading to flood infiltration could distort inward-opening doors thereby increasing FRR substantially and preventing wall or glass failure.
- Other flood actions require further exploration because they might have significant impact when they manifest.
- The results have limited applicability due to the focus on modern residences in England. Timber-frames in Suffolk and knarled flint in Norfolk, for example, are common in flood-vulnerable areas of coastal, eastern England. Structures made from reinforced or non-bonded masonry are also not covered by this dissertation.

Although the specific results and vulnerability matrices in this dissertation could not be readily transferred elsewhere and could not be readily applied to all flood situations, the techniques, methods, and lessons learned could be developed for other locations and residence types.

Sources on residence flood vulnerability management before, during, and after flood actions impact a residence tend to offer comprehensive advice on the possibilities which exist, yet rarely develop tools for determining which option might be the most appropriate in given circumstances. As with many decision-making dilemmas, defining the most appropriate option depends on the criteria being considered and the most important criteria according to the judge. Potential analysis strategies which could be used, irrespective of the perspective taken, are presented here for residence flood vulnerability management.

For example, during a flood, an occupant's inclination is often to seal a residence in order to prevent flood water infiltration and DS2. The goal of sealing is questionable because Chapters 9 and 10 indicate that glass and wall failure may occur at low $f_{diff} \approx 1\text{-}2$ m. Since glass failure leads to DS3 and wall failure leads to DS4 or DS5, sealing to prevent DS2 could result in worse damage than without sealing. A residence might need two options: to seal if ΔP_{max} is forecast to be below a certain level and to unseal if ΔP_{max} is forecast to be above a certain level. If the forecast is uncertain or falls within the range where the choice to seal or not to seal is ambiguous, then this approach presents challenges.

The simplified decision-making dilemma in such a circumstance is illustrated in Table 12. Sealing yields outcomes of low loss (DS1), moderate loss (DS2), or high loss (DS3, DS4, or DS5) whereas not sealing always yields the outcome of moderate loss (DS2). Two other issues must be considered in reaching a recommendation: the ease of implementing a decision and the ease of changing the outcomes in Table 12.

Table 12: Decision-making Matrix for Sealing if ΔP Forecast is Uncertain

Flood ↓ Decision →	Prevent Infiltration (Seal)	Permit Infiltration (Do Not Seal)
f_{diff}-v combination would break glass or walls.	Outcome is DS3, DS4 or DS5.	Outcome is DS2.
f_{diff}-v combination would not break glass or walls.	Outcome is DS1 or DS2.	Outcome is DS2.

Overall, as long as appropriate flood resistance techniques are implemented for a residence, permitting flood water to enter might be simpler, longer-term, safer, and more effective than attempting to decide when to seal and ensuring that sealing is completed properly. Flood management, however, should not be considered in isolation because some flood resistance techniques have non-flood-related drawbacks while others have non-flood-related benefits. Furthermore, whether or not occupants would accept flood water entering their residence, and would adapt their lifestyle and properties to make this option work, is a difficult sociological question.

Table 12 shows that the DS4 or DS5 outcome is partly linked to the choice made regarding infiltration. The flood failure flowchart (Figure 4) therefore displays the sequence in which mitigation options should be considered because decisions in one box would influence decisions in subsequent boxes. The flood failure flowchart combined with the vulnerability matrices provides a useful tool for determining the order in which mitigation options should be chosen.

Another decision-making matrix, for the choice of post-flood restoration of residence components, was developed, as shown in Table 13. In this case, the choice is for residence components such as staircase banisters, furniture, and cupboard doors:

- Replace components: use cheap components and replace them after each flood.
- Remove components: make all components transportable to upper storeys or to another site and ensure that adequate flood warnings and assistance for transporting the components are given.
- Dry and clean components: use flood resistant components.

Analysis suggests that the "replace components" option might often be viable. Tradeoffs amongst the options are noted and a new interpretation of "resilient reinstatement" is proposed.

Table 13: Decision-making Matrix for Post-Flood Restoration of Residence Components

Option → Flood damage ↓	Replace Components	Remove Components	Dry and Clean Components
DS2 or DS3	Outcome is replacement.	Outcome is removing and returning.	Outcome is drying and cleaning.
DS4	Outcome is replacement.	Outcome is removing and returning; possibly some replacement.	Outcome is drying and cleaning; possibly some replacement.
DS5	Outcome is replacement.	Outcome is replacement.	Outcome is replacement.

In addition to assisting with decision-making for managing flood damage to individual residences, the techniques described here contribute to developing community-wide flood management strategies, particularly in terms of highlighting the importance of f_{diff} and v. For example, structural flood defences not only tend to decrease the population's preparedness for flooding but might also exacerbate the damage from f_{diff} and v in floods. Residence layout in a community also influences the extent to which f_{diff} and v manifest in a flood.

Awareness of the detrimental effects of f_{diff} and v should lead to flood management and community design strategies which seek to diminish the impacts of these hazard parameters during a flood. In considering flood management, though, care must be taken to avoid exacerbating other community-wide problems such as crime, road safety, and vulnerability to other natural hazards.

Analysis techniques, both quantitative and qualitative, using this dissertation's research have been illustrated. Possibilities for application to flood vulnerability management for modern residences in England have been described yielding decision-making tools and techniques. Due to conflicting objectives and uncertainties, the same recommendation is unlikely to emerge for every circumstance. A consistent basis for judgement and selection of options is now available and the potential consequences of a decision pathway may be described.

14. Conclusions

The achievements of this dissertation are summarised by matching the results with the stated objectives. Recommendations for further study are given for refining the vulnerability matrices and the flood failure flowchart and for applying them for risk analysis.

This dissertation illustrates that significant improvements could and should be made in the manner in which society manages natural disaster risk, especially regarding flood damage to modern residences in coastal, eastern England. The techniques developed could be expanded beyond the work in this dissertation but could also be adapted to other flood situations, to other types of vulnerabilities, and to risks from other natural hazards. The tasks are complex, requiring a breadth and depth of knowledge which is likely to be beyond the capability of a lone researcher. Nonetheless, through collaboration and persistence, research and application related to reducing society's vulnerability to disasters will ultimately reduce losses and save lives.

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