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An overview of flood actions on buildings

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Abstract

This paper presents an overview of flood characteristics with respect to their applicability for estimating and analysing direct flood damage to buildings. The approach taken is to define "flood actions" as acts which a flood could directly do to a building, potentially causing damage or failure. This definition expands the traditional approach of analysing flood damage to buildings which often focuses on damage from slow-rise flood depth.

Flood actions may be energy transfers, forces, pressures, or the consequences of water or contaminant contact. This paper defines and categorises flood actions on buildings, indicating methods of quantification. The actions are classified in the following categories with respect to relative importance for flood damage assessment.

- High relevance and relatively predictable: Lateral pressure from water depth differential between the inside and outside of a building, lateral pressure from water velocity, and water contact due to slow-rise depth.
- Relevance varies and relatively predictable: Buoyancy.
- Relevance varies and difficult predictability: Capillary rise, erosion, debris, turbulence, waves, other velocity actions, other chemical actions, nuclear actions, and biological actions.

Due to the highly localised effects of some of the flood actions in the third category, coupled with their potentially significant impact, prediction of their impact on overall flood damage may be challenging. Awareness of their existence assists in developing an understanding of the uncertainties in flood damage estimation and analysis and in indicating areas which new research should tackle. In particular, work is needed in order to fully understand the physical processes by which flood damage arises and, hence, how flood damage may be prevented.

Keywords: Buildings; Flood; Flood actions; Flood damage; Forces; Pressures

1. Introduction

Analyses of direct flood damage to buildings often focus on damage from water contact. Water depth in slow-rise floods tends to be the flood characteristic most frequently analysed in detail. Some arbitrary choices of duration are sometimes considered too. This paper summarises flood characteristics less commonly examined in detail with respect to their applicability for estimating and analysing direct flood damage to buildings. Indirect flood damage—such as business interruption, days lost from work, and changed spending patterns—is not classified but would be an important subject for further work.

Characteristics related to direct damage include forces, pressures, chemical reactions, and other impacts

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which a flood could directly impose on a building. Collectively, they are termed "actions" in order to create an all-encompassing vocabulary for this paper. Flood actions describe acts which a flood could do directly to a building, potentially causing damage.

Full analysis of flood actions would permit damage from potential flood events to be estimated and calculated more comprehensively and would allow the uncertainties to be properly acknowledged. First, however, the flood actions must be described and classified qualitatively in order to understand them and their potential impacts. This paper presents an overview for defining and categorising flood actions on buildings, indicating some methods of quantification.

2. Flood damage assessment methods currently used

Slow-rise flood depth tends to be the characteristic of floods most frequently correlated with damage. "Slow-rise" implies that a large hydrostatic pressure differential between the inside and outside of a building does not occur. The dominant effect of the flood is assumed to be slow-moving water which contacts a building and objects.

The Flood Hazard Research Centre (FHRC) at Middlesex University, London has completed extensive studies estimating UK flood damage. FHRC's work focuses on depth-damage curves using slow-rise depth. Their major publications are in the form of manuals (N'Jai et al., 1990; Parker et al., 1987; Penning-Rowsell et al., 1992; Penning-Rowsell and Chatterton, 1977; Suleman et al., 1988). These manuals provide depth-damage curves for various land use categories and also consider two arbitrary flood durations: less than 12 h, termed short, and more than 12 h, termed long.

Other variables are considered at times by FHRC. Suleman et al. (1988) incorporated clean-up costs into the depth-damage calculations. N'Jai et al. (1990) used results from FHRC (1983) which describe the flood depths for which caravans and chalets would float and the chance of destruction for floating dwellings. Penning-Rowsell et al. (1992) list percentages by which to increase the flood damage values in the case of a salt water flood. The assumption is a simple contrast between salt water flooding and fresh water flooding.

Penning-Rowsell et al. (1992) briefly mention velocity's impact on flood damage, from research by Clausen (1989). Clausen (1989) concludes, based on empirical data from mainly the Dale Dyke dam failure in Sheffield on 11 March 1864, that:

- $v < 2$ m/s or $f \times v < 3$ m^2/s yields only "inundation damage";
- $v > 2$ m/s and 3 m^2/s $< f \times v < 7$ m^2/s yields "partial damage"; and
- $v > 2$ m/s and $f \times v > 7$ m^2/s yields "total destruction".

These original results from Clausen (1989) are not exactly the same as reported by Penning-Rowsell et al. (1992). Clausen (1989) notes that using the $f \times v$ variable, also prominent in Sangrey et al. (1975), has little theoretical justification. A physical meaning for this variable is not considered, although it may relate to momentum = mass $\times v = \rho_w \times$ volume $\times v = \rho_w \times$ flood horizontal area $\times f \times v$. ρ_w is constant while flood horizontal area could be considered constant leaving $f \times v$ as the variable.

Clausen (1989) does identify the main hazard parameters of interest for estimating flood damage as water depth, flow velocity, bed shear stress, dynamic forces (flow momentum, stream power, depth times speed), rate of flood rise, and debris potential of the landscape. She states that flood duration is a significant factor, but does not include it as a separate parameter.

In discussing flood velocity, Penning-Rowsell (1981) states, without supporting evidence, that:

> The part played by flood water velocities in producing damage is assumed to be small except in rare cases of structural failure. The more minor effects of velocity are generally measured by the depth variable.

He further suggests that duration is similarly unimportant while sediment loading "affects clean-up costs" and sewage contamination "has been assumed to affect damage values" (Penning-Rowsell, 1981). Meanwhile, Green and Parker (1994) write "Assuming that damage data is standardised for depth then, for direct damages, velocity and sediment loads appear to [be] the next most critical determinants". Overall, the FHRC studies note the importance for damage of flood parameters other than depth but do not analyse them as comprehensively as they analyse depth.

In the UK, but outside of FHRC, Black and Evans (1999) undertook an empirical exercise which analysed insurance claims from seven UK floods during the 1990s. To characterise the floods, depth, duration, velocity, contaminating substances, salinity, and season (summer or winter) were considered. Comprehensive data on the flood events were available for only depth and season. Results were presented as tables of losses in monetary terms, also including the total sum insured in monetary terms as a variable.

Commercial firms develop and apply flood loss models for the UK. Muir-Wood (1999) describes the East Coast UK Storm Surge Flood model developed by Risk Management Solutions Inc. (RMS). Depth and duration are considered for calculating losses along with "A velocity damage modifier for depths in excess of 1.5 m, declining exponentially with distance from the source of flood water" (Muir-Wood, 1999). RMS also markets a UK River Flood Model (RMS, 2001) which covers England, Scotland, and Wales. The model includes "separate damage relationships for river inundation and for direct rain flooding...Inundation vulnerability functions relate damage to flood depth, and direct rainfall vulnerability functions relate damage to rainfall intensity" (RMS, 2001).

Toothill (2002) describes a European flood model developed by EQECAT, a division of ABS Consulting, which includes a probabilistic storm surge model for coastal, eastern England between the Humber Estuary area and the Thames Estuary. This model is currently being revised and updated. The only hazard parameter considered is slow-rise flood depth and losses are provided in monetary terms for the area affected, which can be adjusted to indicate insurance losses.

Many non-UK studies also focus on depth, such as Smith and Greenaway (1980) for Australia; DeGagne (1999) for Manitoba, Canada; Reese and Markau (2002) for Schleswig-Holstein, Germany; Smith et al. (1981) for South Africa; and USACE (1993) and USACE (2000) for the USA. Flood characteristics other than depth and duration, however, often receive more prominence than in the UK, as illustrated in Table 1.

Table 1
Examples of studies of non-depth flood damage studies outside the UK

References	Geographic area	Flood hazards considered
Beck et al. (2002)	Luxembourg	Depth and velocity
Black (1975)	USA	Depth and velocity
CH2M Hill (1974)	Willamette Valley, OR, USA	Depth and velocity
Child of ANUFLOOD (1998), Smith (1991), and Zerger (2000)	Australia	Depth with velocity as an optional input.
Hubert et al. (1996)	France	Depth and duration
Islam (1997)	Bangladesh	Depth, duration, velocity, and salinity were considered to different degrees for different flood types along with damage due to "storm".
Kato and Torii (2002)	Japan	Depth, sediment depth of deposited sediment, and duration.
Sangrey et al. (1975)	Elmira, NY, USA	Depth and velocity.
Smith and Greenaway (1994)	Mackay, Queensland, Australia	Depth, velocity, and wave height.
Torterotot et al. (1992)	France	Depth and duration

As a further example, USACE (1998) describes the impact of velocity-induced hydrodynamic pressures when a Nutwood, IL river levee overtopped without breaching in 1993. Two dwellings collapsed and two dwellings partially collapsed due to failure of concrete foundation walls built to raise the buildings above potential flood levels. USACE (1998) proposes a floodproofing matrix delineating thresholds believed to be important for different damage scenarios:

f_{diff}: shallow (<0.9 m), moderate (0.9 to 1.8 m), or deep (>1.8 m)
v: slow (<0.9 m/s), moderate (0.9 to 1.5 m/s), or fast (>1.5 m/s)
Flash flooding: yes (less than 1 h) or no
Ice and debris: yes or no
Site location: coastal or riverine
Soil type: permeable or impermeable

Three sets of structural characteristics are also provided.

Justification for the categories is not provided, but USACE (1997) notes that most buildings would collapse for f_{diff}>0.9 m. USACE (1998) further suggests that for f_{diff}>0.9 m, the building would need to be designed to resist both hydrostatic and buoyancy forces. This $f_{\mathrm{diff}}=0.9$-m threshold may come from experimental results in USACE (1988).

USACE (1995) describes water loads (hydrostatic and hydrodynamic), debris impact loads, soil loads, wave loads, and uplift pressures as factors in structural flood damage. With respect to water loads, USACE (1995) suggests that only hydrostatic loads must be considered in designing for $v<1.5$ m/s, while floodproofing measures would be economically ineffective for v>3.0 m/s. For $v<3.0$ m/s, "dynamic effects of the moving water may be converted into equivalent hydrostatic loads" with the excess depth proportional to v^2 (USACE, 1995).

Additionally, Smith (1994) and USACE (1996) write overviews on developing depth-damage functions. Smith (1994) notes that velocity may be a concern in rare instances and provides building failure data from Black (1975). USACE (1996) suggests that velocity, duration, sediment, frequency, flood warning, and building characteristics are factors which influence flood damage too.

This review has illustrated that the most detailed studies on direct flood damage have quantified almost exclusively the relationship between depth and damage curves, sometimes with an arbitrary duration modifier. Non-depth parameters are suggested as being important but are not analysed as thoroughly and as systematically as slow-rise depth.

Moreover, estimations of direct flood damage tend not to include an understanding of the physical mechanisms which result in flood damage to buildings. Instead, the flood parameters are described and the damage is described without a detailed explanation of how the former leads to the latter. This traditional approach is needed and is appropriate for many uses, but a knowledge gap remains to be filled.

In particular, causes of damage beyond slow-rise flood depth require detailed investigation. Damage may result from energy transfer, forces, or pressures leading to effects on buildings including wall failure, doors being forced open, glass breaking, roofs collapsing, or foundations being undermined. The next step towards this investigation is a thorough understanding of what a flood could impose on a building in order to elicit a response from the building. The next section presents an overview of categorising such flood "actions".

3. Overview of flood actions

3.1. Introduction

This section identifies and classifies flood actions on a building by providing an overview of qualitative and quantitative characteristics of flood actions. The material is illustrative, indicating those flood actions which should be considered, possible approaches for considering them, how they interrelate with other flood actions, and how the flood actions interact with buildings. The importance is in the qualitative classification which permits patterns to emerge and, as seen in Section 4, a hierarchy to be developed regarding the most important flood actions for assessing direct flood damage.

3.2. Hydrostatic actions

Two forms of hydrostatic action exist: lateral pressure and capillary rise.

The lateral pressure imparted by a depth of water against a building is:

$$\begin{aligned} &\Delta P = \rho_{\mathrm{w}} g (f_{\mathrm{diff}} - y) = \Delta P_{\mathrm{hydrostatic\ at\ }y=0} - \rho_{\mathrm{w}} g y \\ &\text{for } h \leq y \leq f_{\mathrm{diff}} \\ &(\text{where } y = 0 \text{ is the base of the building}) \\ &\Delta P = 0 \text{ for } y > f_{\mathrm{diff}} \end{aligned} \tag{1}$$

Eq. (1) may be considered for an entire building or for only part of a building, such as a glass window or timber door. Fig. 1 uses a window to depict possible variations of Eq. (1):

(a) Water covers the entire window (or building) on one side yielding a linear pressure.
(b) Water rises partway up the window (or building) on one side.

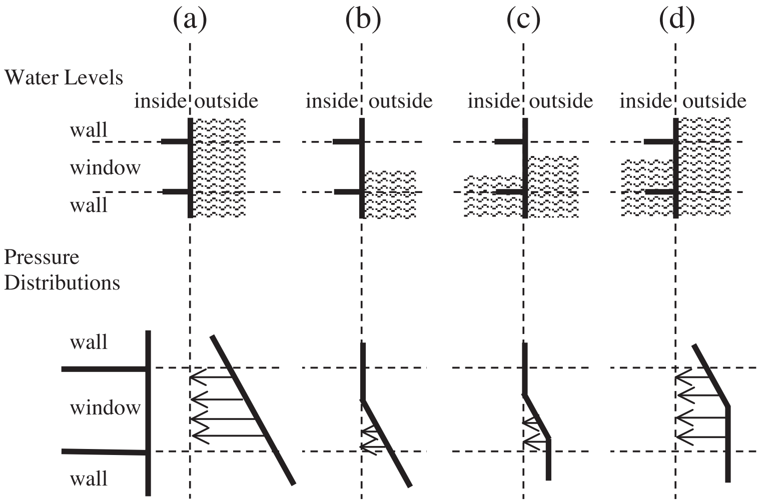

Fig. 1. Water levels and pressure distribution levels on building component in each situation.

(c) Water rises partway up the window (or building) on both sides, but to different y-values on each side.

(d) Water entirely covers the window (or building) on one side and rises partway up the other side.

The same ΔP is imparted to the part of the building being considered whether the water pressure is greater on the outside or inside.

Capillary rise inside a building's components which water has contacted could cause contact damage beyond the level, which the flood water contacts during the flood. Hoffmann and Niesel (1995) write "capillary effects occur in pores between about 0.1- and 100-μm diameter" and they indicate that the pore sizes of, for example, masonry units and render fall within that range. They note that "accessible pore volume and portion of capillary-active pore sizes" are important parameters to consider in determining height of capillary rise through a material. For a brickwork wall, Hoffmann and Niesel (1995) provide a series of equations requiring several empirical parameters for calculating maximum rise height, but they do not estimate typical values. Huelman and Corrin (1997) suggest 0.45 m as an approximate upper limit for capillary rise following a flood, depending on the building's materials.

Capillary rise may also occur in soil, above the water table. Buildings which encounter capillary water may absorb it resulting in damage. Whitlow (1983) suggests that soil saturated with capillary water may occur up to 0.5 m above the water table. Partial saturation with capillary water may occur more than 10 m above the water table for fine soils such as clay.

3.3. Hydrodynamic actions

Five forms of hydrodynamic actions exist: three actions related to velocity (including turbulence) and two actions related to waves.

The lateral pressure imparted by water flowing around a residence may be taken as $\Delta P = 0.5\rho v^2$ for a first-order approximation. This value represents the dynamic pressure due to steady flow of an inviscid, incompressible fluid with negligible heat transfer. This pressure occurs at the stagnation point of a fluid flowing around a bluff body, but may be used for ΔP over a flat wall, such as of a house, as a first-order approximation.

Localised changes in v, and therefore ΔP, occur when water flows around corners of a building or through gaps. A building which withstands the $0.5\rho v^2$ direct pressure may succumb to the local variations, such as suction forces, or may be affected by resulting erosion (Section 3.4).

Turbulence is irregular fluctuations in v, in either or both the magnitude and the direction. Eddies, vortices, surface choppiness, gusts, and rapid but short-lived changes in f or f_{diff}, all distinct from waves, may result. Turbulence can be highly variable over short spatial and temporal scales making quantitative prediction difficult.

Non-breaking waves' peaks and troughs will respectively increase and decrease the pressures and total force exerted on a building. Peaks can add a maximum force approximately equivalent to the hydrostatic force while troughs may decrease the total force by up to 40%—beyond these limits, the wave would break (USACE, 1984). The exact change in total force depends on the ratio of wave height to water depth which is less than about 0.70 for nonbreaking waves (USACE, 1984). ΔP at any point on the building will obviously change in proportion to the depth of water raised or lowered by the wave's peak and trough, respectively. The rate of change of forces and pressures depends on the wave's period.

Waves breaking in, over, through, or near a building can impart large pressures compared with other hydrodynamic actions. Lewis (1983) records that in Chiswell in coastal, southern England, "in December 1978 and in February 1979 waves overtopped the [shingle] bank with such force that several buildings were damaged". The peak dynamic pressures of breaking waves can be "as much as 15 to 18 times those calculated for non-breaking waves [but these values] should be used with caution and only until a more accurate method of calculation is found" (USACE, 1984). Lloyd and Harper (1984) use USACE's (1984) method to calculate ΔP generated by breaking waves for different scenarios. The variations they consider are:

- Flood depths of 0.5, 1.0, 1.5, 2.0, and 2.5 m.
- Bed slopes of 0, 1:20, and 1:50.
- Two exposure conditions: a sheltered bay and an ocean front.

Peak static pressure, peak dynamic pressure, and wave height are calculated. At $f = 0.5$ m, peak dynamic pressure is just under 50 kPa for most variations while at $f = 2.5$ m, peak dynamic pressure is above 500 kPa for most variations.

3.4. Erosion actions

Moving water may cause erosion by scouring away soil from the sides or bed along which the water flows. Baker (1988), Bull (1988), Carter (1988), Hamill (2001), Komar (1988), Nelson et al. (2000), Rooseboom and le Grange (1994), and Whitehouse (1998) describe erosion and scour analysis. This paragraph is based on their findings. Two principal phenomena occur: entrainment of sediment in water and horizontal movement of the entrained sediment. The main water parameters involved in such analysis are f, v, and ρ_{w}, although volumetric flow rate and kinematic viscosity are considered at times. The main sediment property is an index representing grain diameter but sediment density and grain cross-sectional area may be included. Bed roughness, which changes due to erosion, is a factor too. The erosion mechanisms usually cited are lift and drag forces, but turbulence may produce instantaneous upward forces large enough to cause entrainment. Turbulence underneath waves could lead to sediment entrainment and transport too.

Water seeping through soil may physically move the soil. Ubell (1995) and Whitlow (1983) describe the seepage action which occurs as water infiltrates through soil. This force per unit volume is equal to $\rho_{\mathrm{w}}g$ multiplied by the hydraulic gradient. Ubell (1995) writes "The seepage force acting on the soil particles will cause them to move if not opposed by other greater forces acting in the opposite direction". Water may destabilise soil on slopes causing landslips which would destabilise buildings or damage them from direct impact (see other papers in this special issue).

3.5. Buoyancy action

The buoyancy force is a function of the submerged volume of the object, in this case the building. This volume equals the volume of water which the building displaces, i.e. $A \times f$. Thus, the buoyancy force is $\rho_{\mathrm{w}}gAf$. This buoyancy force is an uplift force which could result in the building, or parts of it, floating. Hydrodynamic actions or the hydrostatic lateral pressure may then displace the floating building or parts, potentially causing damage, destabilisation, or complete destruction (FHRC, 1983; Black, 1975; Sangrey et al., 1975).

3.6. Debris actions

Three forms of debris actions exist: static actions, dynamic actions, and erosion. Debris refers to solids in the flood, so chemical, nuclear, and biological actions (Section 3.7) may be relevant too.

At times, the solids may be such a prominent part of a flood wave that the flow is no longer considered to be a water flood. Costa (1988) provides one example of a simple rheologic classification of flows (Table 2). Mainali and Rajaratnam (1991) and Newson (1989) each provide more complicated schemes focused on the higher sediment concentrations. LACOE (1997) illustrates the immense impacts which debris flows may have on buildings as well as on lives and landscapes.

Static debris actions would occur due to sediment accumulating externally or internally to a building. USACE (1984) writes “the forces exerted on a wall by soil backfill depend on the physical characteristics of the soil particles, the degree of soil compaction and saturation, the geometry of the soil mass, the movements of the wall caused by the action of the backfill, and the foundation deformation”. In a flood, the soil backfill would be sediment deposited by the flood. USACE (1984) and Thorley (1969) provide equations for the different forces exerted in a form for which the force imposed equals $0.5\rho_{\text{soil}}gy^2\alpha$. y represents the height of the soil backfill or deposited sediment. α is determined from soil properties and scenario geometry such as the verticality of the building element subject to the forces. USACE (1984) and Thorley (1969) provide data tables for calculating α.

Dynamic debris actions would occur when debris moved by water impacts a building. The impact could be from outside, such as a cow or car. The impact could also be from inside, such as a couch or table floating and hitting the ceiling, an internal wall, or a window. Dynamic debris actions would be either concentrated forces or distributed pressures. An example of a force, concentrated and applied with shock, is a log floating in moving water which impacts a building. Likewise, Lewis (1999) states that during storm surges in Chiswell in southern England, “waves hurl stones and pebbles, causing their own impact damage to roofs and windows”. An example of a distributed pressure applied over a relatively long duration is a hyperconcentrated or debris flow flowing around a building.

Debris could cause severe erosion, such as pebbles or household items being dragged along with the flow and gouging out soil from the sides or bed of the flow channel. The consequences of erosion would be similar to those noted in Section 3.4.

3.7. Non-physical actions

Sections 3.2–3.6 describe physical flood actions. Three forms of non-physical flood actions exist: chemical actions, nuclear actions, and biological actions. Some overlap exists between physical flood actions and non-physical flood actions.

As illustrated in Section 2, flood damage is frequently estimated by considering only the chemical actions which occur when water contacts an object. An example of a chemical consequence is rusting. Physical consequences may result too, such as timber floor boards warping. Additionally, flood-induced humidity may cause damage, even if flood water does not contact the damaged residence (Crichton, 2002). The chemical (contact) action would be from water vapour rather than water.

Flood water may be contaminated with sewage, petrol, oil, paint, household cleaners, or industrial chemicals. Any corrosiveness or flammability in the contaminants could result in chemical damage to residences. A full propane tank or a vehicle’s petrol tank colliding with a residence may result in an explosion. Additionally, the vapour from flood water contaminants may cause damage even if the contaminated flood water does not contact the damaged residence.

Table 2
A simple classification scheme for flows (from Costa, 1988) (Assuming silt and clay content <10%)

Flow	Sediment concentration in entire flow		Bulk density (kg/m^3)	Major sediment-support mechanism
	By weight	By volume		
Water flood	1–40%	0.4–20%	1010–1330	Electrostatic forces, turbulence
Hyperconcentrated	40–70%	20–47%	1330–1800	Buoyancy, dispersive stress, turbulence
Debris flow	70–90%	47–77%	1800–2300	Cohesion, buoyancy, dispersive stress, structural support

Water is a good conductor of electricity. This chemical action in the form of energy is frequently fatal in floods and has the potential to produce electrochemical reactions, which damage buildings; for example, by breaking down render or paint.

Nuclear actions would be much rarer, occurring, for example, if nuclear fuel becomes a contaminant. An example is in eastern England where a nuclear power plant is sited just above the shingle beach at Sizewell, Suffolk. A highly improbable but catastrophic event during which a storm surge severely damages this structure might have a small potential for imparting nuclear actions during the flood.

Biological actions include microorganisms which thrive in damp conditions, particularly moulds and fungi. Floods could also bring animals in contact with buildings which normally would not be encountered, such as jellyfish. Macrovertebrates—including fish, sharks, and reptiles—may impart significant physical forces on buildings if these animals are brought by a flood into the proximity of buildings.

3.8. Summary and interactions

To summarise, the proposed typology for flood actions on buildings is:

1. Hydrostatic actions (actions resulting from the water's presence):
    - lateral pressure from flood depth differential between the inside and outside of a building;
    - capillary rise.
2. Hydrodynamic actions (actions resulting from the water's motion):
    - velocity: moving water flowing around a building 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,
    - nuclear actions,
    - biological actions.

Interactions and combinations must also be considered. For example:

- As implied in Section 3.5, uplift due to buoyancy reduces the lateral hydrodynamic pressure required to move a building (Black, 1975; Sangrey et al., 1975).
- Chemical actions may corrode materials such as brickwork, glass, timber, or PVC, reducing the ΔP from physical actions required for failure.
- Water saturation may soften materials such as finishes or timber, reducing the ΔP from physical actions required for failure.
- Physical parameters such as flood water pressure and temperature at a point in the flood influence the rates and consequences of chemical reactions, such as explosions.
- Chemical reactions, such as acid mixing with water, influence physical parameters such as flood water temperature and density.
- Contaminants such as sewage or oil produce floods with differing physical and chemical properties.

Larson (1999) describes other noteworthy phenomena. Although the effects fall into the categories set out here, they are important enough to highlight separately. During a storm surge flood, a sudden shift in wind direction may permit the sea to swiftly drain away in a phenomenon known as an ebb surge. The physical forces and pressures created by the sudden retreat of water can exceed those imparted by the ingress of water into a community. As well, powerful gusts of wind, spikes far above the 3-s mean, may destabilise a building under pressure from the flood's lateral pressures.

4. Relative importance of flood actions for flood damage assessment

Lateral pressure from f_{diff} and v shows trends at various spatial scales, including at the community or city level. f, f_{diff}, and v or their ranges may be estimated by hydrodynamic models and a reasonable level of predictability at useful spatial and temporal scales can be achieved with such models (e.g. Kelman et al., 2002; Thomalla et al., 2002). This predictability leads to information helpful for estimating medium-to-large-scale damage patterns in a flood event. These lateral pressures also have a high relevance to the damage outcome from a flood since they could lead to structural failure.

Analysis of these actions must include chemical actions from water contact. The reason is that if structural collapse does not occur due to the lateral pressures, then damage would certainly occur due to slow-rise flood depth. Additionally, the lateral pressures may cause only non-structural damage, such as breaking glass, so damage due to f could still be important. When structural failure does occur, though, the impact from f_{diff} and v may dwarf any impact from f alone. The detailed investigation needed to determine the relative impacts of both the lateral pressures and f is achievable at a spatial scale the size of a community or city with appropriate models (e.g. Kelman et al., 2002; Thomalla et al., 2002).

The relevance of buoyancy varies. Timber buildings may float if not anchored properly (Black, 1975; Sangrey et al., 1975), but masonry buildings tend to be securely anchored and would not usually float. Mobiles/caravans are so poorly fastened that they frequently float, becoming debris hazards (e.g. FHRC, 1983). Buoyancy is also relevant for vehicles, people, trees, boats, household items, and other such potential "debris".

The relevance of capillary rise varies. When a storey is flooded, the repair process is generally to completely redecorate the entire storey, irrespective of how high the water rose above f (e.g. Fig. 2). In such cases, the effect of capillary rise is negligible. Damage from chemical action due to f would supersede damage from capillary action.

Other cases may occur where capillary rise transcends storeys, although none were found in the literature or in the field. If such cases were to occur, then damage could increase substantially as a result of capillary rise. For example, Crichton (2002) notes special cases of cavity wall insulation damaged by capillary action along with "strawboard wall boards which can have a capillary effect of several metres". As well, damage in cases where flood water does not directly enter a property could be exacerbated by capillary rise. No such cases were documented in the literature, but capillary rise is not a phenomenon specially looked for in flood damage assessments. Another possibility is that damp-proof membranes in good condition prevented capillary rise from causing extensive damage in these cases. To establish the effect of this phenomenon, more attention could be paid to instances of flood damage claims where flood water has not entered a building.

Fig. 2. Apparent capillary rise inside a flooded building, Keighley, UK, November 2000 (Plaster over the entire storey has been stripped away).

Even in cases in which capillary rise has the potential for augmenting flood damage, swift action in drying a property could prevent much of the damage. Similarly, any structural collapse would obscure capillary rise effects and would supersede capillary rise damage.

Damage from the remaining actions—including erosion, debris, turbulence, chemical actions, nuclear actions, and biological actions—may be absent or may be the most prominent cause of damage for a given flood scenario. Their specific impacts are generally highly localised in space and time. For example:

- A gate being opened or closed, and thereby permitting or impeding high v down a slope, could make the difference between scour undermining a foundation or not.
- A car impacting one house could damage it leaving its neighbours unscathed even though all properties experience similar f, f_{diff}, and v.

- Swift drying and thorough disinfecting of a flooded building prevents mould (EA/CIRIA, 2001).

More generally, non-structural damage from these actions would be superseded by structural damage from lateral pressures. Structural damage from these actions, however, could supersede structural damage from lateral pressures. The transition between structural and non-structural damage for these actions occurs at a highly localised level. Therefore, larger-scale estimation of damage from such actions is difficult, although for each action scenarios could be assumed and the consequences could be investigated.

From this discussion, the actions are classified in the following categories with respect to relative importance for flood damage assessment.

- Lateral pressure from f_{diff} and v along with water contact from f should be considered in estimating damage from most floods. These actions frequently have high relevance and can be predicted in a manner applicable to large-scale loss analyses.
- Buoyancy can be predicted for large-scale loss analyses but its relevance varies depending on the buildings and objects affected by the flood.
- The relevance of the remaining actions (capillary rise, erosion, debris, turbulence, waves, other velocity actions, other chemical actions, nuclear actions, and biological actions) varies depending on the exact form in which the action appears and the consequences from other potentially relevant actions. These actions frequently cannot be predicted in a manner applicable to large-scale loss analyses.

The duration of each flood action must also be considered in analysing its impact.

Avoiding detailed analysis of many of the flood actions described introduces uncertainties into any damage estimation or analysis. For example, as noted in Section 3.3, wave pressures may exceed other hydrostatic and hydrodynamic pressures by an order of magnitude, so waves may not be ignored if they are expected to occur. Additionally, other actions may not be entirely neglected due to their potential importance in certain scenarios.

As flood damage is examined in more detail, more data and experience become available. Observed damage could be matched with estimated damage to better quantify both the damage and the uncertainties and to identify the origin of the uncertainties. The principal factors leading to uncertainties may be extracted and targeted for detailed analysis. Such knowledge could then be applied to developing modifiers to damage functions, such as a factor by which to multiply damage depending on the set of actions which are present in the specific circumstances. The current tendency to focus on damage from f due to slow-rise floods provides a needed basis, but a more comprehensive approach would be useful for flood damage estimation and analysis.

5. Conclusions

The specific extent to which flood actions other than slow-rise depth affect direct flood damage has not been considered to the level of detail afforded to slow-rise flood depth. Nonetheless, strong recognition exists of the importance which the other flood actions play in flood damage to buildings. Due to the highly localised effects of some of the flood actions, coupled with their potentially significant impact, prediction is challenging. Awareness of their existence assists in developing an understanding of the uncertainties in flood damage analysis and in indicating areas which new research should tackle.

This paper has provided an overview identifying and categorising flood actions in order to suggest their relative importance for direct flood damage assessment. These categories indicate the current capability available for introducing more flood actions to flood damage analysis. A poor capability for considering the flood actions over a relatively large space scale does not necessarily imply low impact where they do manifest. Therefore, more work is needed in order to fully understand how flood damage arises and, hence, how flood damage may be prevented.

Symbols used

A	plan area of a structure [m^2]
f	flood depth [m]
f_{diff}	flood depth differential [m]

g	acceleration due to gravity [9.80665 m s^{-2}]
ΔP	pressure difference [Pa]
v	velocity [m s^{-1}]
y	distance upwards from a set reference point [m]
α	factor for forces on a structure due to deposited sediment [no units]
ρ_w	density of water [kg m^{-3}]
ρ_{soil}	density of soil [kg m^{-3}]

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