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ORIGINAL PAPER

An innovative micro-scale approach for vulnerability and flood risk assessment with the application to property-level protection adoptions

Balqis M. Rehan[1]

Abstract Economic damage assessment for flood risk estimation is established in many countries, but attentions have been focused on macro- or meso-scale approaches and less on micro-scale approaches. Whilst the macro- or meso-scale approaches of flood damage assessment are suitable for regional- or national-oriented studies, micro-scale approaches are more suitable for cost–benefit analysis of engineered protection measures. Furthermore, there remains lack of systematic and automated approaches to estimate economic flood damage for multiple flood scenarios for the purpose of flood risk assessment. Studies on flood risk have also been driven by the assumption of stationary characteristic of flood hazard, hence the stationary-oriented vulnerability assessment. This study proposes a novel approach to assess vulnerability and flood risk and accounts for adaptability of the approach to nonstationary conditions of flood hazard. The approach is innovative in which an automated concurrent estimation of economic flood damage for a range of flood events on the basis of a micro-scale flood risk assessment is made possible. It accounts for the heterogeneous distribution of residential buildings of a community exposed to flood hazard. The feasibility of the methodology was tested using real historical flow records and spatial information of Teddington, London. Vulnerability curves and residual risk associated with a number of alternative extents of property-level protection adoptions are estimated by the application of the proposed methodology. It is found that the methodology has the capacity to provide valuable information on vulnerability and flood risk that can be integrated in a practical decision-making process for a reliable cost–benefit analysis of flood risk reduction options.

Keywords Flood risk management · Micro-scale flood damage assessment · Property-level protection · Flood risk assessment · Vulnerability curve · Decision-making

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1 Introduction

Flood damage and risk assessments provide important information in developing an effective long-term flood risk reduction plan. The aim of flood risk assessment is commonly beyond identifying factors that may shape vulnerability of human population to flood hazard (James 2013)—it seeks to address the probabilistic nature of consequential flood damage to support decision-making through both structural and nonstructural planning. In this regard, flood risk assessment addresses an extensive range of flood events and their potential consequences to quantify the expected economic loss (Hall 2014). Though the assessment of expected damage of a range of possible flood events is important in risk-oriented approaches to flood design and flood risk management (Schroter et al. 2014), it still remains a challenge and is perceived as one of the biggest hurdles in flood risk assessment (Rasekh et al. 2010).

The term 'risk' in a technical assessment of flood impacts is predominantly defined as the product of flood hazard and consequences. The flood consequences can be defined as the state of vulnerability of the elements at risk to flooding. There have been various attempts among researchers to define 'vulnerability' in the context of flood consequences. This study perceives 'vulnerability' as the degree to which the elements at risk are susceptible due to their exposure to flood impacts, whereby the exposure of the elements at risk is influenced by their ability to respond towards minimizing the impacts (Balica et al. 2013; Merz et al. 2010a, b). By this definition, 'vulnerability' is regarded as the composite element of 'susceptibility' and 'exposure'. The many different definitions of 'vulnerability' and the difficulty to reach consensus on the definitions may stem from the different contexts, aims, purposes and spatial scales of studies. Also, the physical elements that contribute to total flood losses are possessing ambiguous relationships that may influence the conceptualization of vulnerability.

'Vulnerability' can be represented as the expected economic damage given a possible flood loading. Vulnerability assessment involves generally three main steps: specifying or identifying the flood loading that is substantial enough to cause flood damage, simulations of flood extent through spatial analysis, and estimation of economic flood damage. The degree of vulnerability of a community to a range of flood loadings can be illustrated in the form of a vulnerability curve that may be used in further assessment of flood risk. Whilst the route to estimate flood extent and damage of a single flood event is common, estimating economic damage for a wide range of flood events is challenging. The convention of the former usually needs to be repeated when flood damage due to multiple flood events is to be assessed (e.g. US Army Corps of Engineers 2016). This has resulted in many studies to focus only on a minimum number of flood events for the economic damage estimations of flood risk assessment (e.g. Meyer et al. 2012; Zhou et al. 2012; Arrighi et al. 2013).

It is a common practice in flood risk assessment that flood hazard and vulnerability are assessed in two separate modules, but linked together by a determining variable. The determining variable is usually taken as return periods, i.e. the inverse of exceedance probability. Conventionally, the probability distribution function (PDF) that governs the estimation of the exceedance probability is assumed to exhibit a stationary characteristic, where the PDF is time invariant. Over the past decade, there have been concerns over the potential effects of anthropogenic climate change to flooding that have led to the growing interests of suitable nonstationarity models to represent the changing PDF of flood events (e.g. Olsen 2006; El Adlouni et al. 2007; Leclerc and Ouarda 2007; Seidou et al. 2012; Katz 2013; Salas and Obeysekera 2014). Although the studies that consider potential nonstationary

characteristics of flood hazard have been quite advance, attempts to integrate the nonstationary characteristics of flood hazard with the physical-based vulnerability assessment when estimating risk under nonstationary conditions are scarce. Often, changes in flood risk are introduced as increases in percentage of intensity of flood loadings or the return period (e.g. Zhou et al. 2012; De Kok and Grossmann 2010) and neglect nonstationary distributions.

Another challenge in flood risk assessment is that many established approaches to estimate economic flood damage focus on macro- or meso-scale assessment, where coarse resolutions of spatial information and area-based approximations are used (e.g. Apel et al. 2009; de Kok and Grossmann 2010; Feyen et al. 2012; Jonkman et al. 2009). The two approaches are important for national or regional flood maps establishment or for a broad-scale flood risk management plan development. However, the rough estimation of flood damage through the approaches tends to jeopardize the accuracy needed for local-scale applications (Apel et al. 2009). For example, high-detail information is required when addressing community-based risk reduction options, such as local flood embankments or property-level protections. To ensure that sufficient details of spatial characteristics with the heterogeneous nature of the elements at risk are captured in flood risk assessment, a micro-scale level of assessment should be sought (Messner et al. 2006; e.g. Molua 2012; Kebede and Nicholls 2012). The micro-scale assessment is now becoming more adoptable with the greater accessibility of high-resolution DEM from LiDAR. Extensive data collection of ground surveys may also be eliminated with the application of GIS processing tools and available aerial imagery and surveys (Mason et al. 2011), promoting a practical application of the micro-scale approach.

Taking forward the challenges and gaps highlighted above, the aim of this paper is twofold. The first aim is to propose a methodology that can systematically capture the flood vulnerability curve. Novel flood damage functions for a micro-scale application are introduced within the proposed methodology. This includes a flood damage function considering property-level protection (PLP) adoptions. These functions are constructed to allow automated computations of total direct economic damage given a wide range of possible flood inundations and possible alternative PLP extents. The methodology is intended to provide a vulnerability curve that can directly be used for risk estimation under both stationary and nonstationary conditions of flood hazard. The second aim of this study is to implement and test the feasibility and adoptability of the methodology using real information of a local area and associated historical extreme flows. In particular, flood risk under stationary condition is estimated using the configured vulnerability curve and the PDF of extreme flows.

2 Methodology, study area and input data

Extreme flow discharge is chosen as the determining variable for the vulnerability assessment. An advantage of having flow discharge as the determining variable is that the vulnerability curve can directly be integrated with the PDF of extreme flows to estimate flood risk. The modelling steps developed for the vulnerability assessment follow the source–pathway–receptor approach (SPR) (Messner et al. 2006; Merz et al. 2010a, b). The 'source' of flood hazard is represented by the peak discharge, the 'pathway' is associated with the physical characteristics of the topographical area, and the 'receptor' is described by the heterogeneous nature of the residential buildings in the flood-prone area.

This study only considers individual residential buildings located diversely across the floodplain as the flood receptors. Although buildings as flood receptors can be distinguished into different sectors or sub-categories (e.g. commercial category such as hotels and restaurants, or household category such as terrace, bungalow and flat) (e.g. Penning-Rowsell et al. 2010; Arrighi et al. 2013). However, it is difficult to include the many different sectors or sub-categories in flood damage studies due to the extensive data required that may be expensive. Datasets related to private households are relatively easy to access as compared to commercial buildings, which explains one of the reasons why private households have often been considered in flood damage studies as opposed to include the many sectors or sub-categories (Merz et al. 2010b). For a preliminary assessment, this study focuses on residential sector average values to estimate the losses.

In terms of flood indicator, there has been an international acceptance for the use of inundation depth to indicate flood damage (Jongman et al. 2012). Whilst it is acknowledged that other factors, such as velocity or contamination, can influence the magnitude of flood damage, these are hard to model in the context of vulnerability assessment (Merz et al. 2010b). Flood depths and associated economic damages are commonly captured as depth–damage curve. Many countries have developed their own version of depth–damage curve (Jongman et al. 2012). This study adopts a depth–damage curve for the estimation of total flood damages corresponding to a range of maximum inundation level, which is applied for each affected residential building. By assuming a horizontal plane on the flood-prone area due to the inundation (e.g. De Kok and Grossmann 2010; Di Baldassarre 2012), the associated flood depths of each building may vary as a result of varying ground floor elevation levels.

A modelling chain to establish the vulnerability curve is framed in Fig. 1. The modelling chain incorporates several modelling approaches to generate stage–damage and stage–discharge relationships. Primary data comes from LiDAR DEM and depth–damage relationship. For the case where PLP adoptions are considered, a PLP extent has to be defined. The stage–discharge relationship links the extreme flow discharges with maximum inundation levels, whilst the stage–damage relationship links the maximum inundation levels with expected damages. It is important to note that the terms 'stage' and 'level' indicate the same meaning, i.e. water level above a specified reference point. By integrating information from the stage–discharge relationship and the stage–damage relationship, the
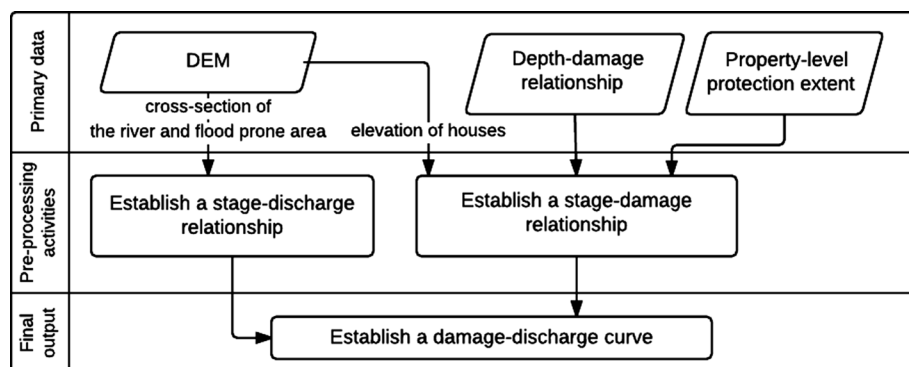

Fig. 1 Work flow to establish vulnerability curve in terms of damage–discharge relationship

vulnerability curve of residential buildings to flooding in the form of a damage–discharge curve can be established.

The micro-scale approach to assess vulnerability opens the opportunity to evaluate potential risk reduction of PLP adoptions. There has been wide acceptance that PLP can help reducing flood risk. This can be seen from participations of local authorities in providing financial aid, such as the partnership funding in the UK (Great Britain, Department for Environment, Food and Rural Affairs (2016a, b). The Department for Environment, Food, and Rural Affairs (DEFRA) of the UK through a cost–benefit appraisal of PLP suggests a 20-year return period of protection extent as the most cost-beneficial investment (Great Britain, Department for Environment, Food and Rural Affairs 2016a, b). Whilst this suggestion may be useful in developing a flood risk management strategy, a vulnerability assessment that is tailored to the distinct characteristics of a local area under study would improve the cost–benefit appraisal. Moreover, vulnerability, risk or cost-effectiveness of PLP adoptions considering locations of individual buildings may provide better information to homeowners, as uptake of PLP is finally the choice of homeowners. To the author's knowledge, studies on benefits of implementing PLP in a flood-prone community have focused on damage assessment per unit area (e.g. Moel et al. 2014; Boettle et al. 2011), but not on individual buildings.

2.1 Pre-processing activity to configure stage–discharge relationship

A stage–discharge relationship for flood risk assessment is commonly configured through an application of a hydraulic model. There is a wide variety of commercial and noncommercial hydraulic packages available to estimate the stage–discharge relationship. Whilst any model might be used for the stage–discharge relationship configuration, the accuracy of the model should represent the scale of the area under study. A 1D or a combined 1D and 2D hydraulic model typically requires an input of one or more cross sections that are perpendicular to the river to capture the dominant physical terrain of the floodplain area. A sufficient number of cross sections can be determined by the relative width and length of the river stretch under study. The recommended distance between two cross sections is 10 to 20-fold of the river width (Di Baldassarre 2012). This means that the narrower width of the river and the shorter river length of the study area require less cross sections for the hydraulic assessment.

A pre-processing activity to configure a stage-discharge relationship in this study adopts the Conveyance and Afflux Estimation System (CES-AES) software developed and made available by HR Wallingford (2011). The model is suitable for small- to medium-sized rivers under the assumption of a steady flow. The development of the model was based on large experiments, and the model has been tested and validated against a number of full-scale rivers in the UK and overseas with measured and laboratory data (Knight et al. 2010). Other approaches can also be adopted to establish the stage–discharge relationship for this study, as long as the assumption of a planar water level across the study area holds.

2.2 Pre-processing activity to configure stage–damage relationship

Another pre-processing activity of the current framework deals with establishing a stage–damage relationship. Stage–damage relationship provides values of expected total economic damage caused by a range of flood inundation levels. A discrete algorithm [Eq. (1)] is proposed to estimate the total economic damage (D_1) by aggregating the direct

damage to residential buildings at ground elevation levels located lower than a given maximum flood inundation level. Under the assumption that the direct damage to individual buildings will incur once the maximum flood inundation level exceeds their ground floor elevation level, and that no development or new residential buildings are built for all flood scenarios, the total economic damage is considered to be driven by: 1) the density of residential buildings (P) at each incremental ground elevation level (g) below the maximum inundation level (n) and 2) the flood depths (h) associated with the range of ground elevation levels of the residential buildings.

$$D_1 = \sum_{i=0}^{n} \left(P_{gy=n-i} D_{hz=i+1} \right), \quad i < n \text{ and } i, \ n \in \mathbb{Z}_{\geq 0}. \tag{1}$$

Incremental discrete elevation steps from a level that resembles a threshold of no damage ($i = 0$) to a level that represents the maximum inundation level ($i = n$) are established. Indexes y and z derived from i are also introduced for referencing of g and h, respectively. After the discrete steps are established, the associated information of D_{hz} and P_{gy} with reference to the indexes is gathered from a reliable source, such as LiDAR and aerial map, or National archive of ordnance survey. The information is then stored in a look-up table accordingly. The reference points of y and z enable the algorithm to search for values of the associated variables in solving the equation. The way the equation is designed also implies that an equivalent length of input datasets of h and g of a similar interval is required for a successful automated calculation. Furthermore, the interval should be equally spaced. For example, a density of residential buildings distributed on 20 equally spaced ground floor elevation steps should be accompanied with economic damage values also of 20 equally spaced flood depth steps with a similar space unit. With the focus on micro-scale damage estimations, appropriate small interval should be assigned.

Economic damages to individual building considering a range of flood depths (D_h) can be obtained by using a suitable depth–damage relationship. A number of established depth–damage relationships for a number of countries have been formed through empirical data of past flood events or synthetic data of simulated flood events (Jongman et al. 2012). Either one approach can be used for the assessment provided that the depth–damage relationship is constructed based on the national prices of the case study area. Following the assumption of a residential sector average of the economic values, a uniform depth–damage relationship across all affected buildings is used. In cases where economic damage to different types of residential buildings or nonresidential buildings may contribute significantly to the total economic damages, the algorithm can easily be expanded to accommodate the different depth–damage relationships. For a specified maximum inundation elevation level at index n, the total economic damage is quantified by summing up the paired multiplication of P and D values associated with g and h, respectively.

In accounting for PLP adoptions, this study assumes that the PLP measures provide resistance to flood damage up to a certain depth of protection from ground floor elevation levels of the buildings, respectively (e.g. Moel et al. 2014). Equation (2) presents the extension of Eq. (1) in an attempt to estimate the total economic damages given a certain extent of PLP adoptions. Similar to Eq. (1), Eq. (2) comprises discrete variables as inputs, and the outcomes are presented in the form of a stage–damage relationship. Two reference points in relation to the PLP adoptions are introduced. One indicates the highest ground elevation level of buildings equipped with the PLP measures (HGEL), whereby the equation will automatically assign that all buildings located on lower ground elevation levels are also

equipped with the PLP measures. Hence, this reference point represents the spatial extent of PLP adoptions in the community. Another reference point refers to the lowest ground elevation level of buildings equipped with the PLP measures (LGEL). Several assumptions are put forward to allow for a smooth recursive computation of Eq. (2):

- Buildings that are protected by the PLP measures are assumed to be individually resistant to flooding up to a standard height above their ground floor elevation levels.
- When a maximum inundation level is lower than the protection threshold of the LGEL, all buildings are considered safe from damaging consequences.
- Once the maximum inundation level exceeds the threshold of the HGEL, all protected buildings are considered to be directly affected by the flooding.
- When a maximum inundation level is higher than the HGEL but lower than the protection threshold of those buildings and that the maximum inundation level exceeds protection thresholds of buildings located at lower grounds, the buildings located at lower grounds are considered to be directly affected.

Under the above assumptions, three constraints attributed to i are introduced in the equations:

- i_f denotes the elevation level of the protection threshold on buildings located on the LGEL.
- i_p denotes the HGEL of the buildings equipped with PLP measures.
- i_m denotes the elevation level of the protection threshold on buildings located on the HGEL.

Using the notations as in Eq. (1) and the newly introduced notations above, the total damage (D_2) associated with a maximum inundation scenario (n) is denoted in Eq. (2).

$$D_2 = \begin{cases} 0, & \text{for } n < i_f \\ D_{i_f < n < i_p}, & \text{for } i_f < n < i_p \\ D_{i_f < n < i_p} + D_{i_p \leq n < i_m}, & \text{for } i_p \leq n < i_m \\ D_1, & \text{for } i_m < n, \end{cases} \tag{2}$$

where

$$D_{i_f < n < i_p} = \sum_{i=i_f}^{n} \left(P_{gy=n-i} D_{hz=i+1} \right);$$

$$D_{i_p \leq n < i_m} = \sum_{i=i_P}^{n} \left(P_{gy=i+1} D_{hz=n-i} \right).$$

D_2 is equal to D_1 when the maximum inundation level is higher than the maximum extent of PLP adoptions. i_p and the values associated with it are obtained directly from the lookup table of the base case. i_f and i_m are governed by the selected standard resistant threshold depth of the PLP adoptions and hence require users to first define the elevation levels of

the threshold in reference to the HGEL and LGEL. These can easily be identified from the previously compiled data stored in the look-up table. Both Eqs. (1) and (2) provide flexibility to the users to specify the height of the interval of the elevation/depth. However, the selected height of interval needs to be appropriately small enough to capture the impact and effects of the PLP adoptions. A large interval height may not be able to discern the effects of PLP adoptions and the base case.

2.3 Establishing the vulnerability curve

A vulnerability curve in the form of a damage–discharge relationship is the main output of the proposed methodology for the economic damage assessment. To capture an appropriate range of damaging flow discharges that can cause direct damages to residential buildings of a study area, the boundary of the study area should first be delineated through investigations of flow magnitudes, extreme flow probability and ground elevation levels of the residential buildings. The range of expected economic damages caused by the flow magnitudes are then estimated by first determining the corresponding maximum inundation levels. This is undertaken by interpolating the stage–discharge curve of the area. Using the maximum inundation levels, the expected economic damages associated with the range of maximum inundation levels are then obtained by interpolating the stage–damage curve. Finally, the vulnerability curve is established by linking the flow discharges assigned earlier with the associated economic damages.

2.4 Risk estimation

Flood risk as a manifestation of flood hazard and vulnerability is computed by integrating a range of probability-weighted damage (PWD). The PWD is a combined product of vulnerability and the associated probability. Whilst vulnerability here refers to the damage–discharge relationship, the flood probability is represented by a probability distribution function of an annual maxima flow series that follows the conventional approach of stationary assumption. The integration of the range of PWD produces an economic value of annual risk. Because of the stationary assumption, the annual risk can be considered as an average annual damage due to the time invariance of the PDF over the appraisal period.

Equation (3) presents the annual risk equation, with the vulnerability function as $D(q)$, the PDF as $f(q)$, and the extreme flow magnitude as q. Appropriate lower (q_{min}) and upper limits (q_{max}) for the integration should be used when solving the equation. The q_{min} refers to the threshold of no damage identified through a stage–discharge relationship interpolation, whilst the q_{max} is identified from the delineation of the study area boundary. A scenario with a PLP adoption requires the q_{min} to be adjusted to account for the standard protection threshold.

$$Risk = \int_{q_{min}}^{q_{max}} D(q) \cdot f(q). \tag{3}$$

This equation is solved through a quadrature rule where the determinant flow discharges are evenly spaced in the interval. The associated damage and probability are then quantified for the PWD. The summation of the PWD over the interval returns the annual risk.

3 Application

3.1 Study area

The feasibility of the methodology is tested using spatial information of an urban area in Teddington, London. The area chosen is a residential community area located adjacent to a riverbank. Figure 2 shows a raster image with a range of colour codes to distinguish the elevation levels extracted from LiDAR DEM data. The DEM was obtained from the Environment Agency (Great Britain, Environment Agency Geomatics 2011) and has a resolution of 0.1 m × 0.1 m. The area is located upstream of the Greater London, where tidal influence is not a major concern due to a high standard protection that is already in place for the Greater London (Wicks et al. 2011). The area is also a strategic location due to its location just downstream of the Thames at Kingston gauging station. This permits the use of long records of historical flow discharges from the station to be used for this study.
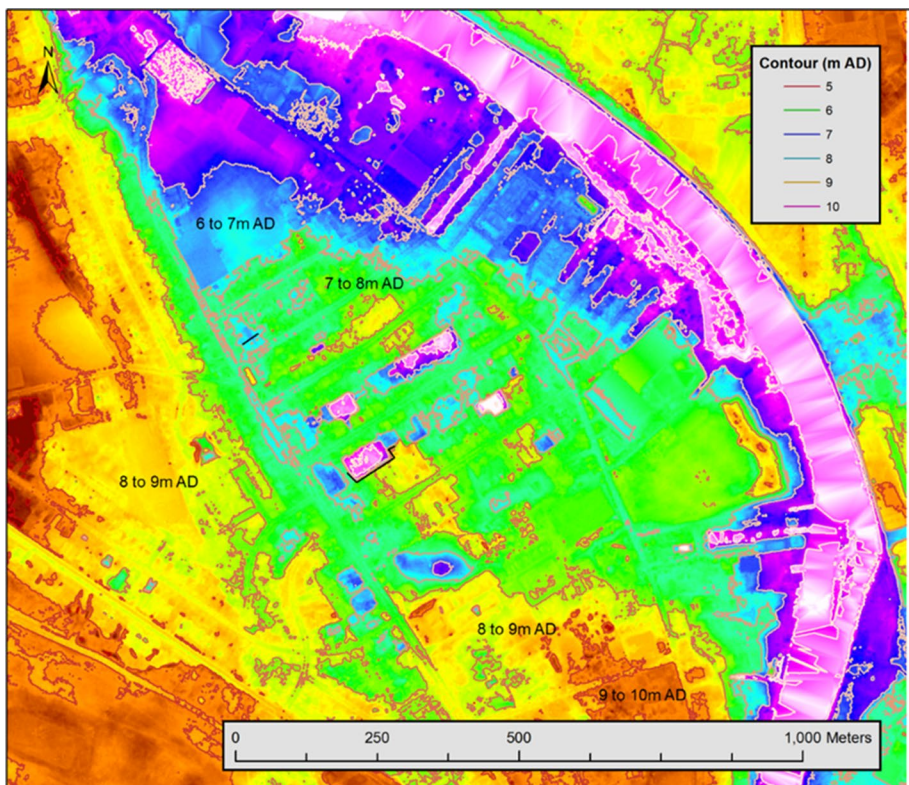

Fig. 2 Raster map of part of Teddington area. Upper right legend shows the different contour elevations, where the pink-coloured bend shape on the north-east of the area represents the river stretch, and the flood-prone area of the case study is located west from the river. The flood depths were determined by subtracting the elevation level from a given maximum inundation level

3.2 Data and parameter estimation

3.2.1 Establishing the boundary of the study area

The definition of risk as a product of probability of hazard and consequences means that a low probability flood hazard that result in significant economic damages may have an equivalent PWD to that of a higher probability flood hazard that result in minimal economic damages. For example, an exceedance probability of 0.99% that causes £ 10,000 economic losses has the same PWD as an exceedance probability of 99% that causes £ 1000,000 economic losses, i.e. PWD equals to £ 9999. The combined hazard and vulnerability can also yield a very small estimate of risk that can be rounded to zero. This can happen due to a far located residential area from the source of hazard or a high elevated area that can only be reached by a relatively higher water level. In order to optimize the model run, prior investigations on the appropriate spatial extent/input data is necessary. The spatial extent should include the elements at risk that may significantly contribute to the risk estimates and those that are not may be neglected in the risk estimates.

In this study, the spatial extent is determined by examining the links between the primary factors that contribute to flood risk. This includes investigating the probability of a range of extreme flows and identifying the corresponding flow levels that may trigger direct damage to residential properties. Whilst the probability distribution of extreme flows is constructed through the flood frequency analysis, the distance of the nearest buildings to the river is identified by overlaying a satellite imagery to the raster DEM of the area using GIS tools.

Historical mean daily flows from year 1883 to 2013 were extracted from the Thames at Kingston gauging records. The annual maxima flow series of the water years, i.e. October–September, of the dataset are then fitted into the generalized extreme value (GEV) distribution by maximum likelihood estimation method using R package of ExtRemes (Gilleland and Katz 2016). The relationship between flow discharges and return period, i.e. the inverse of exceedance probability, from the statistical model fitting is depicted in Fig. 3. Further analysis of the historical evidence showed that a 2003 flood event caused approximately 460 m^3/s peak discharge, corresponding to a probability of exceedance of 10% (i.e. approximately 10-year return period). Transforming the discharge into stage showed that the flood magnitude will not cause overspill to the Teddington area, despite the historical
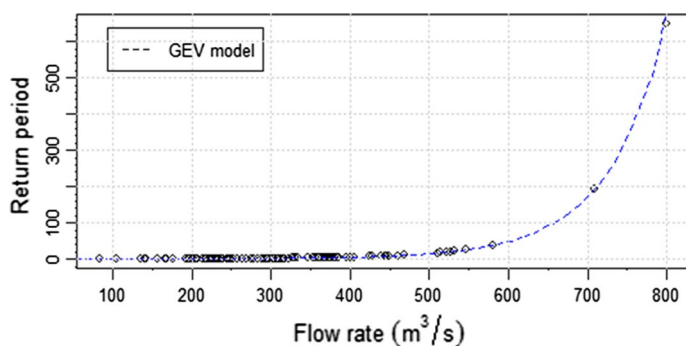

Fig. 3 Probability curve of Thames at Kingston AM flow records. The plots represent observations, whilst the blue line represents fitted stationary GEV model

evidence that different parts of the Thames Catchment had experienced damage from the 2003 flood event (Marsh and Harvey 2012). It is found that the corresponding stage for the peak discharge is 4.77 m AD, which is the bankfull stage of the river adjacent to the Teddington area (Centre for Ecology and Hydrology 2014).

Further investigation on the flood-prone area from DEM reveals that the ground floor elevation level of the nearest residential buildings to the river is at 5.6 m AD. The buildings' vertical and horizontal distances from the river are approximately 1 m and 225 m, respectively. Considering the 2003 flood event, these spatial characteristics indicate that direct flood damage of the residential buildings of the community can only occur when the peak discharge is significantly higher than 460 m^3/s. This is good news for the community. However, to obtain a clear distinction between vulnerability curves of scenarios with and without PLP adoptions from the application of the methodology proposed, it was agreed that the case study area should pose a relatively higher degree of exposure. It was then decided that the terrain of the study area is to be slightly modified to aggravate flood impact to the area. This was made by increasing the elevation of the riverbank to modify the stage–discharge relationship. After the adjustment, a bankfull stage of 4.77 m AD now corresponds to 120 m^3/s as compared to the initial 460 m^3/s (Fig. 5 in Sect. 4.1). Because of the adjustment, the quantitative end results should be interpreted with caution and should only be focused on the feasibility of the methodology tested.

With the modification to the stage–discharge relationship, a flow magnitude of 1100 m^3/s corresponds to a 0.002% exceedance probability and inundation stage of 7.2 m AD is selected as the maximum possible extent of the study area. The discharge corresponds to a 50,000-year return period. The density of the residential buildings in terms of their ground floor elevation levels is extracted from the overlaid satellite imagery to the DEM with rooftops and chimneys as indications of the locations of the buildings. It is assumed that the elevation levels extracted represent the ground floor elevation levels of the respective buildings.

3.2.2 Data for stage–discharge relationship

The present study area covers an approximately 1-km-long river with a width of 100 m. To configure the stage–discharge relationship, a single cross section is deemed reasonable in accordance with the rule of thumb given by Di Baldassarre (2012). A line perpendicular to the river and crossing through the terrain was established over the LiDAR raster of the study area, and the ground elevation levels were extracted. The ground elevation levels were then transferred into the CES-AES software followed by assigning unit roughness of different land-use types using suggested values from an inbuilt dataset within the software. The so-called roughness advisor that stored the dataset provides sufficient database of information on hydraulic roughness of different surfaces in the form of descriptions and photographs sourced from over 700 references (Knight et al. 2010).

Table 1 presents the different zones established to represent the different land-use types and the associated unit roughness. The unit roughness for the river bed is found to be exceptionally high, potentially due to the relatively shallow depths of the river of the present case study. Manning values may increase substantially at lower depths and can be up to 0.16 at certain rivers (Knight et al. 2010), and it can vary between 0.017 and 0.2 m$^{-1/3}$/s^{-1} depending on the physical characteristics of the flow conveyor (Vorogushyn et al. 2010). Figure 4 shows the elevations of the cross section separated by their zone types. Extreme flow is expected to cause inundation from the lowest elevation near the main channel to the highest elevation level along the cross section.

Table 1 List of zone types assigned and associated unit roughness suggested in the CES-AES software	Zone types and names in parentheses	Unit roughness (m$^{-1/3}$/ s^{-1})
	Riverbank (RBank)	0.0546
	River bed (RBed)	0.102
	Housing plain (housing)	0.0381
	Green area on floodplain (FPlainGrass)	0.021

3.2.3 Data for stage–damage relationship

The height of the interval of the elevation steps and flood depths was selected as 0.1 m, drawn from the LiDAR DEM resolution of the present study area. Given that the computed marginal height between the nearest residential buildings to the river (i.e. 5.6 m AD) and the elevation level of the maximum extent of the study area (i.e. 7.2 m AD) is 2.6 m, the elevation levels for the case study form 11 ascending steps. Table 2 shows the tabulated data obtained for the damage model runs of the status quo condition and with PLP condition. The first column comprises ascending ground elevation levels of the residential buildings located within the boundary of the study area. The second column consists of ascending indexes for the automated computation, whilst column three provides the values of interpolated damages to one residential building associated with a possible range of flood depth. The depth–damage relationship is denoted as D_h in Eq. (1) and Eq. (2). Column four presents the density of buildings associated with the ground elevation levels indicated in the first column. This table acts as the look-up table used for the automated computation of the total damage estimation.

The interpolation of damage for a range of flood depths was made using a depth–damage relationship from the Multi-Coloured Manual (Penning-Rowsell et al. 2010) in which synthetic values are based on 2005 UK prices. The prices include detailed building components (e.g. plumbing and electrical), building fabrics (e.g. furniture, domestic clean-up) and household inventories. The depth–damage relationship available for the UK based on the MCM is limited to a 3-m maximum flood depth, which requires an extrapolation to be made for damage estimates of a higher flood depth. The density of buildings was determined by discretizing the ground floor elevation levels of the residential buildings from

Fig. 4 Cross section of the study area delineated in the CES-AES software for stage–damage relationship. Zones are defined in Table 1

Table 2 Look-up table storing the input data for stage–damage relationship of the status quo condition and with PLP condition

Ground floor elevation level (m AD)	Calculation indices $i, n, z,$ and y	Damage to a residential building associated with flood depths (£) D_h	Number of residential buildings at each elevation level P_g
5.6	1	980	4
5.7	2	18,925	3
5.8	3	28,859	3
5.9	4	32,754	1
6.0	5	33,476	3
6.1	6	34,199	5
6.2	7	34,921	7
6.3	8	35,606	6
6.4	9	36,292	20
6.5	10	36,977	21
6.6	11	37,418	13
6.7	12	37,859	24
6.8	13	38,299	17
6.9	14	39,061	18
7.0	15	39,823	53
7.1	16	40,586	53
7.2	17	41,220	76

the LiDAR DEM of the study area. This is undertaken by overlaying a satellite imagery of rooftops and chimneys of buildings with the LiDAR DEM.

3.2.4 Data for property-level protection

This study assumes that a resistant package of PLP measures when installed to a building can prevent direct economic losses up to 0.6 metres from the ground floor elevation level of the building. The height is a common standard specification for the resistant type of PLP measures used in many studies (e.g. Great Britain, Department for Environment, Food and Rural Affairs 2016a, b; Boettle et al. 2011; Moel et al. 2014). A higher protection level may not withstand the hydraulic pressure when the inundation depth is high, but may be considered with the advancement of technology (e.g. RO/rheim 2004, Arrighi et al. 2013). Assuming a 0.6-metre height of protection implies that there would be no direct damage to the building when the water level is below the height, unlike the case of no PLP adoption. This result in a higher lower limit of integration for the risk estimates [Eq. (3)] for cases with PLP adoptions as compared to without PLP adoptions [Eq. (3)].

To estimate flood risk for conditions with PLP adoptions, the protection extent of PLP adoptions needs to be specified. This was undertaken by first defining a targeted HGEL for the area, followed by determining the associated discharge and return period (RP) using the stage–discharge relationship and probability distribution function. The study considers six alternative protection extents from which the effects of different protection extents can be distinguished. The range of PLP extents are considered to test the usefulness of the proposed methodology. They were determined accounting for information from the flood frequency analysis and from the delineated boundary of the study area. The six protection

extents in terms of return period and the associated stages are as follows: 6.3 m AD (20-year RP), 6.4 m AD (30-year RP), 6.5 m AD (60-year RP), 6.6 m AD (120-year RP), 6.7 m AD (240-year RP) and 6.8 m AD (570-year RP).

4 Results and discussion

4.1 Stage–discharge curve

The resulting stage–discharge curve of the status quo condition is shown in Fig. 5. Note that the curve also represents the stage–discharge curve of conditions with PLP adoptions. It can be seen that the curve is less steep after it reaches approximately 200 m³/s of flow discharge, i.e. approximately a stage of 5 m AD. The cause of the output can be explained by examining the terrain characteristics of the area where the change occurs. The cross section of the study area in Fig. 5 shows that the steep change is a result of a topographical change from the river to the green floodplain area where an increased capacity or water conveyance is expected.

It is assumed that because many buildings are heterogeneously located in the area, the difference of the resulting stage–discharge relationships with and without PLP can be ignored (Apel et al. 2009). Therefore, the stage–discharge curve for conditions with PLP adoptions follows that of the status quo condition.

4.2 Stage–damage curve

The stage–damage relationship configured for the status quo condition is depicted in Fig. 6, along with the stage–damage relationship of a condition with PLP of 20-year return period protection extent adoptions. This protection extent represents the HGEL of 6.3 m AD and implies that all residential buildings located on the HGEL and below are installed with the resistant package of PLP measures. Figure 6 shows that the PLP adoptions effectively reduce the estimated total damage, especially for the higher maximum inundation level. The estimated total damage of each protection extent can be seen to eventually reconcile with that of status quo condition-estimated total damage.

The reliability of the designed damage functions can be verified by simply examining the level at which the two curves start to reconcile, and is compared with that of manual computation. The level at which the total damage of the condition with PLP is
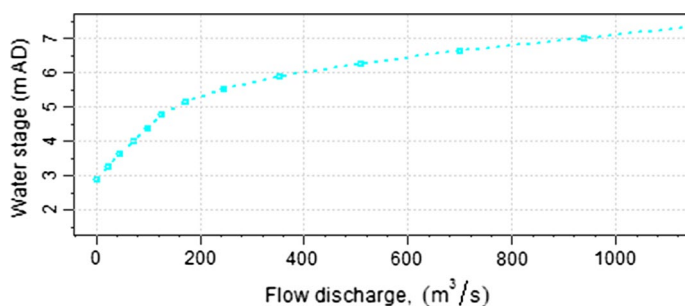

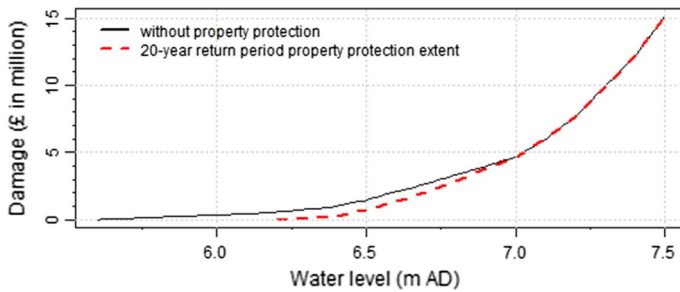**Fig. 5** Stage–discharge curve of the status quo and with PLP conditions

Fig. 6 Stage–damage curves for status quo condition (solid black line) and condition with PLP of 20-year return period protection extent (red dotted line)

equivalent to the total damage of the condition without PLP is when the maximum inundation level is higher than the PLP elevation level of the highest protected residential buildings. For this study, the PLP elevation level of the highest protected buildings are 6.3 m AD + 0.6 m = 6.9 m AD, where a maximum inundation level at 7 m AD implies that all applied PLP measures are no longer functional.

4.3 Vulnerability curve

The stage–discharge and the stage–damage curves for the status quo condition and the conditions of with PLP extent adoptions were interpolated to establish vulnerability curves. The vulnerability curves are influenced by the extent of PLP adopted. Figure 7 shows that in all cases, the total damages are reduced for a higher PLP extent adoption. Furthermore, the curves of with PLP adoptions can be seen to increase in a somewhat similar manner across all six conditions. This is mainly driven by the constant PLP height considered in all cases. Though the reduction in total damages can be seen clearly from stage–damage curves, the curves at some points reconcile with the curve of the status quo. This happens when the maximum flood inundation level completely overtops the protection level associated with the PLP extent considered. This implies that the PLP may become less important when higher-magnitude flood events occur except for buildings located at a higher ground
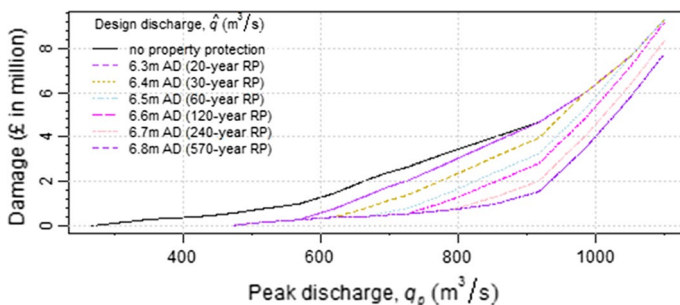

Fig. 7 Damage–discharge curves for status quo condition (solid black line) and conditions with different options of PLP extents (coloured lines)

elevation levels. However, for a relatively lower magnitude flood event the reduction in total damages as compared to the status quo condition can be significantly large.

4.4 Risk estimation

Further estimation of risk for each condition was undertaken using the configured PDF and the established vulnerability curves. The estimated risks in terms of average annual damage for the status quo and six different protection extents are as follows: £ 214,716 for the status quo, and £ 39,044, £ 27,747, £ 21,461, £ 19,509, £ 17,924 and £ 17,462 for the six PLP extents, respectively. The reduction in risks is significant and varies from 82 to 92%. These values consider tangible and direct economic damage of flood impact to residential buildings (i.e. physical damage) and exclude other indirect and intangible damage (e.g. impacts to health, inconvenience of post-flood recovery).

The risk estimation can also be presented by linking the expected annual damage with the expected number of houses affected, and the average flood risk for a building may then be computed. However, presenting the risk to buildings using the average values neglects the main features and aim of the proposed discrete approach. The proposed damage function within the computation captures in an implicit manner the nonuniform risk exposed to individual buildings. Some buildings are expected to be more vulnerable than the others although their longitudinal distance to each other may be small.

5 Conclusions

This study has developed a micro-scale approach to assess the vulnerability of residential buildings to flooding, accounting for direct and tangible impacts and heterogeneous locations of buildings. The methodology integrates a novel approach towards constructing a stage–damage relationship, one of the main components to model the vulnerability curve. The proposed algorithms are dedicated to ease recursive computations involving a wide range of flood scenarios. This means that a parsimonious approach to hydraulic assessment is being put forward whilst detailed spatial information and socio-economic condition of the residential properties up to the individual building level is sought. This enables a faster yet comprehensive output of the vulnerability such that a risk-oriented assessment can be undertaken conveniently. The methodology advances the micro-scale approach to model vulnerability to flooding similar to what is being promoted in Arrighi et al. (2013).

Furthermore, the intermediate results of the stage–discharge and stage–damage relationships, and the outcomes of vulnerability curves and risk estimations from the methodology allow a thorough computation verification. The proposed methodology that is compatible for a local-scale application also has the capacity to assess the vulnerability and risk of a community to flooding involving PLP adoptions. The results from the case study show that the adoption of PLP can reduce the vulnerability and risk of the community to flooding.

The risk estimation within the methodology is predominantly governed by the probability of flood hazard and the potential economic consequences. Whilst the way to estimate the probability of flooding through a stationary-based assumption of flood frequency analysis is generally well practised, the assessment of potential consequences of flooding through a vulnerability assessment depends on the scale of study and often presented as a function of the probability characteristic of the hazard, e.g. the return period. The latter may be due to the prevailing assumption of stationarity in flood frequency analysis.

With concerns over the changing climate amounting, vulnerability may be presented as the economic damage corresponding to extreme flow magnitudes to disassociate it with the stationary assumption of the flood hazard. Extreme flow magnitudes as the exogenous variable allows risk under nonstationary condition to be estimated conveniently using the vulnerability curve as a stand-alone function, along with the nonstationary PDF of the flood hazard. This is aligned with the call to have a more appropriate approach for a practical application of flood risk study concerning a possible nonstationary condition (e.g. Salas and Obeysekera 2014).

The estimated risk from the application of the methodology can further be used to evaluate the benefit of risk reduction and subsequently used for a cost–benefit analysis of different options of PLP extent adoptions. The damage function proposed allows vulnerability assessment of different PLP extents to be undertaken systematically and conveniently and hence readily incorporated into a cost–benefit analysis framework. By specifying a number of alternative protection extents, a range of outputs of vulnerability curves are estimated. The range of vulnerability curve can then be used for a subsequent risk-based options appraisal in seeking the most cost-effective PLP extent. Evaluation of cost-effectiveness of PLP measures can broaden the opportunity for a wider engagement between individual homeowners and local authorities.

The results from the case study indicate the applicability of the methodology for a micro-scale flood risk assessment with a particular focus on direct damage to residential properties. The methodology can be refined to incorporate other predominant sectors and/ or other related direct and indirect damage. These refinements may lead to a more accurate estimation of economic losses and flood risks for the study area of concern. However, the factors that contribute to the damage estimates are locally driven and, therefore, should be considered accordingly.

The methodology proposed may also be extended for other community-based protection measures, such as flood embankments and channel dredging, such that the vulnerability and risk reduction due to the different flood protection options can be undertaken at the micro-scale level. The implicit high-detail information of local representation within the valuation associated with each option may offer a great improvement in flood risk management decision-making. It is also interesting to examine the vulnerability and risk, and the results of the cost–benefit analysis of the different flood risk reduction options under nonstationary conditions. The findings will be insightful in an effort to adapt to uncertain future changes.

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