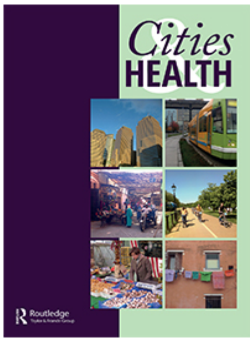

Cities & Health

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/rcah20

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CITIES & HEALTH
https://doi.org/10.1080/23748834.2020.1800161

ORIGINAL SCHOLARSHIP

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Housing, health and energy: a characterisation of risks and priorities across Delhi's diverse settlements

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ABSTRACT
Improved housing has the potential to advance health and contribute to the Sustainable Development Goals. Research examining housing, health and energy use in low-income countries is limited; understanding these connections is vital to inform interventions for healthy sustainable human settlements. This paper investigates the low-income setting of Delhi, where rapid urbanisation, a varied climate, high pollution levels, and a wide variation in housing quality could result in significant energy use and health risks. Drawing on approaches from health and the built environment and existing data and literature, a characterisation of energy use and health risks for Delhi's housing stock is completed. Four broad settlement types were used to classify Delhi housing and energy use calculations and health risk assessment were performed for each variant. Energy use is estimated to be nearly two times higher per household among planned housing compared with other settlement types. Health risks, however, are found to be largest within informal slum settlements, with important contributions from heat and particulate matter across all settlements. This paper highlights intervention priorities and outlines the need for extensive further research, particularly through data gathering, to establish evidence to accelerate achieving healthy, sustainable and equitable housing in Delhi.

ARTICLE HISTORY
Received 1 May 2019
Accepted 16 July 2020

KEYWORDS
Housing; health risks; energy use; Delhi; India; intervention priorities

Introduction

Better housing has the potential to improve health and well-being (Howden-Chapman *et al.* 2012), advance development, especially in low-income countries (Haines *et al.* 2013), and support environmental objectives, notably in relation to energy consumption (Haines *et al.* 2009). Housing interventions have been shown to improve physical and mental health (Thomson *et al.* 2001, Office of the Deputy Prime Minister 2006, Gibson *et al.* 2011, Howden-Chapman *et al.* 2011) and reduce health inequalities (Thomson *et al.* 2013). Energy efficiency in housing is vital for climate change mitigation objectives, with buildings currently accountable for 38% of total global energy usage and 25% of energy-related CO_2 emissions; hence, energy efficiency in homes is crucial to reduce emissions (Wilkinson *et al.* 2007). Improved housing, therefore, has an important role in achieving the United Nations Sustainable Development Goals, particularly Goal 11: Make cities and human settlements inclusive, safe, resilient and sustainable, but also to achieve energy efficiency (Goal 7), combat climate change (Goal 13) and ensure health and well-being for all (Goal 3) (United Nations Development Programme 2015).

Research examining the connections between housing, health risks and energy use in housing has tended to focus on high-income countries with temperate climates that have adopted energy efficiency targets. Research has evaluated the health impacts of strategies and policies for energy efficiency in housing. In the UK, for example, the implementation of insulation in homes has been shown to offer protection against cold-related mortality (Wilkinson *et al.* 2007). However, energy efficiency interventions may also cause unintended adverse health impacts (Shrubsole *et al.* 2014), without due consideration (Davies and Oreszczyn 2012). For example, both modelling (Milner *et al.* 2014) and empirical measurements (Symonds *et al.* 2019) of UK housing indicate energy efficiency improvements are likely to be responsible for increases in indoor radon levels. The health benefits of housing interventions in low-income countries is considered much greater (Wilkinson *et al.* 2009), yet there is a little evidence on the links between energy, health, and housing in these developmental and

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climate contexts – more research is necessary to understand risks and priorities for interventions in these different settings. Housing quality in low-income countries can be extremely varied, and interventions are vital to achieve energy efficiency targets and health goals simultaneously.

This paper aims to investigate housing health risks and energy use in the context of a low-income country and identify where interventions are needed. The city of Delhi, India, was selected as a case study, as it provides an example of a rapidly urbanised city, with unprecedented levels of uncontrolled housing development, which may present significant challenges in providing sustainable and healthy living environments.

Background

India is projected to be the most populous country by 2050, predicted to be home to 20% of the world's population with nearly 1.7 billion inhabitants, and with the urban proportion expected to grow from 31% to 52% during the next four decades (United Nations 2017). Pressures from this rapid growth, along with a disorganised approach to housing provision (Mahadeva 2006), can be seen through a shortage in housing and related infrastructure across Indian cities (Sivam and Karuppannan 2002). The population of the National Capital Territory (NCT) of Delhi has substantially increased over the last century from just under 1 million inhabitants in 1941 to over 16 million in 2011 (Government of India 2011). This growth has coincided with the development of unauthorised and informal settlements, where the slum population is reported to account for 47% of the housing stock (Government of National Capital Territory of Delhi 2008). These settlements suffer from poor quality housing, cramped spaces and a lack of basic services and infrastructure (Goli *et al.* 2011), with significant risks of infection and injury (Ezeh *et al.* 2017).

With this rapid growth, there are also energy challenges. In 2015, India was the fourth-largest energy consumer (after the United States, China and Russia), with energy consumption rates growing annually (U.S. Energy Information Adminstration 2018). International Energy Agency (IEA) Energy Balance Statistics for India state that the residential sector accounts for the largest proportion (38%) of the country's energy use (International Energy Agency 2009). Although per capita energy consumption remains very low, future projections indicate increased electricity use and higher ownership of appliances as incomes increase (Reddy and Srinivas 2009), resulting in higher CO_2 emissions (Rout 2011, van Ruijven *et al.* 2011). Within Delhi, the residential sector is responsible for 45% of electricity sales (Government of National Capital Territory of Delhi 2013). Consequently, this combination of increased appliance usage and housing growth could result in high future demands on energy consumption.

Environmental conditions in Delhi are extremely challenging. Delhi experiences a composite climate (Bureau of Indian Standards 2005), with a large seasonal variation between a cold winter (mean minimum temperatures below 10°C), dry and hot summer (highs up to 45°C) and a humid monsoon period (Indian Society of Heating Refrigerating and Air-Conditioning Engineers). Temperatures are predicted to increase by 3–4°C by 2100 due to a changing climate (Defra, Akhtar 2007, Singh and Dhiman 2012), with heat waves becoming more frequent, risking significant impact on energy consumption through air conditioning (A/C) use (Sivak 2009, Akpinar-Ferrand and Singh 2010) and heat-related mortality (Akhtar 2007). A humid monsoon season coincides with an outbreak of mosquitoes, with vector-borne disease epidemics becoming more likely (Dhiman *et al.* 2010). Outdoor air pollution levels are notoriously high due to generation from vehicles, industry, diesel generators, and brick kilns (Guttikunda and Goel 2013). Delhi's mean annual concentrations of particulate matter $PM_{2.5}$ (PM with an aerodynamic diameter ≤2.5 μm) regularly exceed 100 μg/m^3 (Government of National Capital Territory of Delhi 2013), severely breaching World Health Organization (WHO) air quality guidelines of 10 μg/m^3 (WHO 2006, 2010). Due to both anthropogenic (waste burning for heating) and meteorological conditions, $PM_{2.5}$ winter levels are two to three times higher than summer and monsoon periods (Guttikunda and Gurjar 2012). Furthermore, the effects of rapid urbanisation have resulted in polluted water supplies (Ministry of Environment and Forests Power Government of India 2001), poor solid waste management (Talyan *et al.* 2008) as well as heightened noise pollution (Firdaus and Ahmad 2010). These external factors will have a substantial influence on indoor conditions, and hence household energy consumption and potential health impacts.

Objectives

Rapid urbanisation, significant informal housing provision, increased energy use in the domestic sector, along with a challenging external environment, suggests substantial sustainability and health risks across Delhi's housing. There are, however, opportunities for interventions that could help meet energy and health goals simultaneously. This paper aims to make a broad assessment of health risks and energy use across Delhi's housing to inform priorities for interventions that could improve health and sustainability. As such, this paper aims to answer the following questions:

- What are the housing characteristics of Delhi's housing stock?
- What are the energy use characteristics and principle health risks, and how do these differ across the housing stock?
- What are the priorities for housing interventions to advance health and sustainability goals?

An assessment of Delhi's housing, of this scale and type, has never been completed. Such work is necessary for identifying the key risks and priorities across Delhi, this will help inform avenues for further research as well as pathways for interventions, which then can be utilised by planners, engineers and architects to enable a transition towards a healthy sustainable urban environment.

Methodology

The methodology developed was informed by the fields of public health and the built environment. The work draws on existing data sets and available evidence and applies broad assessments to understand current energy use and health risks across Delhi's housing. An overview of the approach used is shown in Figure 1.

Stratification of Delhi's housing stock

Housing stock models have been widely used in studies assessing city residential energy consumption and potential interventions, with the housing stock generally broken into distinct archetypes based on relevant housing surveys (Kavgic *et al.* 2010). Stratification of the housing stock is useful for both the development and assessment of policies and strategies that can improve health or reduce energy consumption in the given area. We aimed to develop a stratification method of Delhi housing to estimate current energy use and principle health hazards to develop and assess potential strategies.

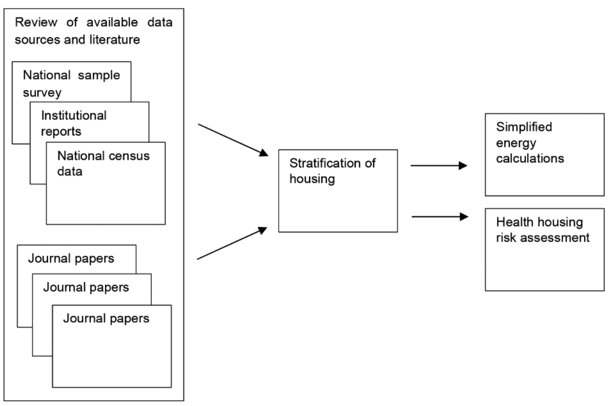

Figure 1. Overview of the methodology.

For the case of Delhi, there is no comprehensive survey that details housing characteristics at the level needed to generate distinct archetypes. The India Housing Census (Government of India 2011) and Housing Condition National Sample Surveys (NSS) (N. S. S. O.-M. of S. & P. I. Government of India 2010a) provide basic details of common construction materials, floor areas, and the number of rooms per dwelling but do not provide detailed data on the built form, such as thermal properties, layouts, or ventilation provision necessary to generate a set of archetypes. The annual Delhi Economic Survey provides a breakdown of dwellings by settlement type in Delhi (Government of National Capital Territory of Delhi 2008) (Table 1). These settlements follow three modes of development: informal, organic and formal, which have different planning jurisdictions. Formal housing areas are planned by governing development authorities or private agencies; these have formal legal sanction prior to development and should comply with building regulations (Sivam 2003). Informal housing is composed of unauthorised colonies, built illegally on private land, and slum settlements, both of which lack legal tenure (Sivam 2003). Organic settlements consist of old urban housing and traditional rural villages, which have evolved over time (Ishtiyaq and Kumar 2011).

The modes of development have a significant influence on the built form and infrastructure characteristics and are connected with different income groups. These distinct modes of development were used as a basis to stratify Delhi housing stock into four settlement types as followed:

(1) High-income planned housing – these are developed by private agencies or the Delhi Development Authority (DDA), and often takes the form of plotted housing and multi-storey flats that comply with building standards and have infrastructure provision (Sivam 2003, UN Habitat).
(2) Villages (including both rural and urban villages) – these have become part of Delhi with urbanisation (Ishtiyaq and Kumar 2011). These are more traditional in style – commonly open-fronted housing with 3–4 storeys, closely packed on narrow streets, and with little natural lighting (Kumar Soni 2011). They lack planned services, are suffering from overcrowding and dilapidation (Ishtiyaq and Kumar 2011), and tend to be occupied by mid- to low-income groups (UN Habitat).
(3) Unauthorised colonies (of which 13% are now regularised and given formal land rights), which are built illegally on agricultural land; information

Table 1. Settlement types in Delhi, from (Government of National Capital Territory of Delhi 2008).

Type of Settlement	Development and Settlement Characteristics	Est. population in 2000 (million)	% of total est. population
JJ Clusters	Arose from encroachment on public/private land. Extremely poor living conditions.	2.072	14.8
Slum Designated Areas	Improved version of JJ Clusters	2.664	19.1
Unauthorised Colonies	Developed on agricultural land by illegal means	0.740	5.3
JJ Resettlement Colonies	Plots allocated by the DDA to resettle JJ clusters from 1975	1.776	12.7
Rural Villages	Will probably be urbanized by 2021. Similar characteristics to rural villages.	0.740	5.3
Regularised- Unauthorised Colonies	Similar characteristics to the unauthorized colony, but with better infrastructure and right to tenure.	1.776	12.7
Urban Villages	Rural villages that fell into urban areas after rapid urbanization	0.888	6.4
Planned Colonies	Planned by DDA or private agencies from the early 1960s.	3.308	23.7
Total:		13.964	100.00

about these housing types is sparse. Infrastructure is provided through regularisation.

(4) Slum or locally known as *jhuggi jhopdi* (JJ) cluster settlements. These are home to the urban poor and are self-built, simple structures without land tenure, which undergo incremental growth with time (Sivam 2003). They are small and tightly cramped dwellings with floor areas no larger than 20 m^2 (Ahmad and Choi 2011), suffering from a lack of services, inadequate ventilation, and poor thermal comfort (Mitchell 2010).

Example photographs of the four categories of settlement types are shown in Figure 2. The various data sets were then linked to the settlements types, by household income, to develop a broad description of the housing in each category. This was cross-checked through field visits and personal correspondence with experts in housing in Delhi.

Figure 2. Examples of category 1: planned housing (top left), category 2: urban/rural villages (top right), category 3: unauthorised housing (bottom left), and category 4: JJ Clusters (bottom right).

Construction and energy use characteristics of settlement types

Dwelling construction materials and energy uses were linked to settlement types via several different sources. Here, we review the available data sources across the settlement types.

Construction characteristics. The Census and NSS show that in the case of all settlement types, the majority of housing is constructed with burnt brick (N. S. S. O.-M. of S. & P. I. Government of India 2010a, Government of India 2011). In the higher income group concrete accounts for 97% of all roofing material (N. S. S. O.-M. of S. & P. I. Government of India 2010a). Details of the material composition used in planned dwellings were based on studies from Kumar & Suman (2013), Ramesh *et al.* (2010), as well as the IT Toolkit EnEff ResBuild India (TERI and Fraunhofer Institute for Building Physics). Little information is available about composition in the unauthorised and urban village settlements and therefore we assume they are similar to the planned dwellings. The material used in the JJ settlements is likely to be much more varied. For example, concrete accounts for less than 50% of roof material in the lowest income group, with metal sheets, stone, canvas, or timber as other predominant materials (N. S. S. O.-M. of S. & P. I. Government of India 2010a).

Energy use and appliances. Both the Census and Housing Condition NSS surveys detail access to electricity and the use of primary cooking fuels. All settlements are likely to use Liquid Petroleum Gas (LPG) as the predominant cooking fuel (Government of India 2011). The majority of households have access to ceiling fans (TERI 2007) (N. S. S. O.-M. of S. & P. I. Government of India 2010b) and the penetration of appliances such as TVs and fridges are similar across settlement types. 99% of houses in Delhi have electricity for lighting (N. S. S. O.-M. of S. & P. I. Government of India 2010a). However, the use of A/C or air coolers is skewed towards high-income settlements, most likely planned dwellings. Ownership of A/C or coolers increases with the monthly per capita expenditure (MPCE) class from 26% of households in the lowest decile to 77% in the highest (N. S. S. O.-M. of S. & P. I. Government of India 2010b). TERI reports higher ownership of A/C in higher housing tax bands with air coolers used predominately in mid-housing tax bands (TERI 2007). 48% of electricity sales in Delhi are domestic consumers (Government of National Capital Territory of Delhi 2013), and it is estimated that 50% of residential electricity use in summer months is due to a combination of ceiling fans, air coolers, and A/C (TERI 2007). The ownership of heating equipment is recorded to be low across all settlement types (TERI 2007).

The available data sources were mapped to the settlement types, these findings were confirmed by experts in the field with experience in the housing in Delhi. A summary of the characteristics of each settlement type can be found in Table 2.

Assessment of household energy use

To assess typical energy consumption across the Delhi housing stock, we performed a simplified energy calculation to estimate energy use for each settlement types, supported by the data and housing characteristics gathered in the previous section. This method considers available data on the ownership of appliances (lighting, cooking, cooling and other end-use), average appliance power ratings, and time in use, and used assumptions on occupant behaviour based on available survey data. This simplified approach allows a broad estimation of energy use and CO_2 per settlement type based on the currently available data. More detailed approaches, such as dynamic building energy simulations or the degree-day method, would require detailed data on building characteristics or a broader range of assumptions, which would require detailed surveying and measurements to perform at the stock level and was thus deemed beyond the scope of this exploratory work.

Total annual energy usage, E_T, is taken to be the sum of the energy use of all appliances, based on the number of appliances of type i, n_i, the power rating of appliance i, P_i and the time of use of appliance i, t_i,:

$$E_T = \sum_i n_i \times P_i \times t_i \qquad (1)$$

CO_2 emissions are then calculated by applying the appropriate carbon intensity coefficients for the fuels used and electricity generation. Energy use from cooking was taken to be the same across all settlement types, based on average LPG usage per month (D'Sa and Murthy 2004). Energy use for lighting and appliances was based on survey data assessing typical appliance use in residential dwellings in Delhi (TERI 2007). Hours of use of cooling appliances (fans, coolers and A/C in occupied bedroom and living rooms) was calculated to be the number of hours when the external temperature exceeded a threshold temperature. The threshold temperature was given by a thermal comfort study in composite climate in India (Indraganti 2011) and the external temperatures were taken from a typical weather file for Delhi (Indian Society of Heating Refrigerating and Air-Conditioning Engineers). Given the low ownership of heating appliances across all income groups, we did not consider this end-use type. Detailed inputs taken for appliance usage, power rating, and carbon intensity can be seen in Table 3. We carried out a sensitivity analysis for the planned settlement type to understand the impact of input variables on the output variable, described in Appendix A.

Assessment of housing health risks

To characterise the distribution of health risks across the settlement types, a risk assessment was completed. Risk assessment techniques are widely established (British Standards Institution 2010) and have previously been used to assess housing health hazards elsewhere (Jacobs 2011). These use expert judgement to assess hazards, and generally consist of three steps; hazard identification, risk analysis and risk evaluation. Although more sophisticated methods exist, such as exposure-response relationships to calculate the disease burden, expert judgement has been a common method due to the lack of data, a wide range of potential hazards and multiple health outcomes. Studies using exposure-response relationships tend to have a narrow or single focus, such as those that review health risks from indoor temperatures (Scovronick and Armstrong 2012). We draw on existing frameworks but adapt them to the level of available data for Delhi.

Hazard identification

Hazards identified for inclusion in the assessment are based on those included in the United Kingdom Housing Health Safety Rating System (HHSRS) (Sverdlik 2011), which is the most extensively developed assessment tool (Keall *et al.* 2010). As the context of Delhi significantly differs, we supplemented the UK HHSRS with additional hazards for particulate matter and vector-borne diseases which may be present in Delhi. The hazards assessed are listed in Table 4.

Risk analysis methodology

A semi-quantitative method was used to characterise the principal health hazards. The method considers the likelihood of occurrence and expected harm from available literature and data sources, experience from field visits and consultation with local experts. A consequence/

Table 2. Typical properties of each settlement type.

Type:	Planned dwellings	Urban/rural villages	Unauthorised colonies	JJ Clusters	Ref
%	24	11	18	47	(Government of National Capital Territory of Delhi 2008)
Description:	- Planned housing built by private agencies or the DDA - Often high rise - Legal tenure & planned services	- Evolved organically over time, with legal tenure - Services introduced as and when without prior planning - 3 to 4 storey houses in close and narrow streets	- Built on illegal land however settlements are becoming regularised with legal tenure - Infrastructure is introduced on as and when basis - Little information on housing style	– 1 to 2 storey buildings, with small ground floor areas (20 m^2) - Self-built and undergo incremental growth - Often only one façade exposed - No legal tenure, apart from in the case of JJ Resettlement colonies	(Sivam 2003, Ishtiyaq and Kumar 2011, UN Habitat, Kumar Soni 2011, Ahmad and Choi 2011, Mitchell 2010)
Rooms	1 x living room 2 x bedrooms 1 x kitchen 1 x bathroom	1 x living room 1 x bedroom 1 x kitchen 1 x bathroom	1 x living room 2 x bedroom 1 x kitchen 1 x bathroom	2 x multi-purpose rooms	(Government of India 2011, Kumar Soni 2011, Mitchell 2010, Government of National Capital Territory of Delhi 2009)
Housing materials	- Wall: Plaster & Burnt Brick - Roof: Brick + Reinforced Cement Concrete	- As planned housing however indications suggest thicker roofs	- Little information but assumed to be as planned housing	Varied: from temporary building materials to brick and cement construction	(Government of India 2011, N. S. S. O.-M. of S. & P. I. Government of India 2010a, Kumar and Suman 2013, Ramesh *et al.* 2010, TERI and Fraunhofer Institute for Building Physics)
Income distributions	- High/Mid-income groups	- Mid/Low-income groups	- Mid-income groups	- Low-income groups	(Government of National Capital Territory of Delhi 2008)
Cooking fuel and separate kitchen	- LPG -Separate kitchen	- LPG -Separate kitchen	- LPG -Separate kitchen	- LPG - No separate kitchen	(Government of India 2011)
Electrical appliances	- TV - Fridge - Lighting	- TV - Fridge - Lighting	- TV - Fridge - Lighting	- TV - Fridge - Lighting	(N. S. S. O.-M. of S. & P. I. Government of India 2010a, TERI 2007, N. S. S. O.-M. of S. & P. I. Government of India 2010b)
Ventilation and cooling systems	- AC & fans - Windows with cross ventilation likely	- Fans & air coolers - Poor levels of ventilation	- Fans & air coolers - Windows with cross ventilation likely	- Fans - Poor levels of ventilation (no or small windows)	(TERI 2007, N. S. S. O.-M. of S. & P. I. Government of India 2010b)
Infrastructure and services	Piped water, toilets and sewage systems	Water tanks, toilets, containment tanks.	Water tanks, toilets, containment tanks	Water by tanker, no sanitation.	
Problems reported:	- High temperatures in top-floor flats	- Overcrowding, congestion, and structural dilapidation - Studies suggest reliance on artificial lighting and extremely poor levels of ventilation	No data available	- No available or low-quality infrastructure and facilities - Overcrowding, poor ventilation and tightly cramped housing	[Ishtiyaq and Kumar, 2011; Kumar Soni 2011; Mitchell, 2010; Nix E, et al., 2014]

Table 3. Assumptions on energy use in dwellings.

Category	Usage	Carbon Intensity
Cooking	13.3 kg LPG per month per household in all settlement types (D'Sa and Murthy 2004), assuming a calorific content of 45,750 kJ/kg (Natarajan *et al.* 2008)	0.2147 kg CO_2 per kWh (Carbon Trust 2011)
Lighting	Estimated from (TERI 2007) to be: Bedrooms – 60 W bulbs 2hrs/day Living rooms 60 W bulbs 5hrs/day Bathrooms 55 W tube lighting 2hrs/day Kitchens 55 W tube lighting 2hrs/day	0.943 kG CO_2 per kWh was assumed (IEA 2007)
Appliances	120 W TVs was calculated in all settlements 5hrs/day (TERI 2007) 200 W refrigerator was assumed to be always on (TERI 2007)	
Cooling	Fans (60 W) turned on in all dwellings when hourly external temperatures exceed 26.2°C during occupied hours in bedrooms and living rooms (Indraganti 2011). The external temperature was taken from a typical weather file for the location of Delhi, commonly used for building simulation (Indian Society of Heating Refrigerating and Air-Conditioning Engineers) Air coolers (200 W) (used in unauthorised and urban villages) and A/C units (1750 W) (used in planned) turned on when external temperatures exceed 28.5 and 31.3°C respectively in occupied bedrooms and living rooms (Indraganti 2011)	

Table 4. Hazards assessed in the Delhi housing stock (from UK HHSRS apart from those marked * which were added for the Delhi stock).

Physiological requirements *Hygrothermal conditions, pollutants*	Psychological impacts *Space, security, light & noise*
• Damp & mould • Heat • Cold • Particulate matter* • Asbestos • CO and combustion products (NO_x, NO_2 SO_2) • Uncombusted LPG • Lead • Radiation • VOCs	• Overcrowding • Entry by intruders • Inadequate lighting • Noise
Infections *Hygiene, sanitation & water supply*	**Accidents** *Falls, electric shocks, fires, burns & scalds, collisions, cuts & strains*
• Vector-borne diseases* • Domestic hygiene, pests, refuse • Food safety • Personal hygiene, sanitation and drainage • Water supply	• Falls baths • Falls level surfaces • Falls on stairs • Falls between levels • Electrical shocks • Fire • Flames, hot surfaces • Collision, and entrapment • Explosions • Position and operability of amenities • Structural collapse and falling elements

probability matrix was developed to rank the risks (Table 5). Such methods are commonly used as a screening tool when many hazards are identified or where data is limited and can provide guidance on which hazards require further detailed analysis or should be treated first (British Standards Institution 2010). The likelihood of occurrence and the expected harm for each hazard was assessed to be either low, moderate, high or severe (or 1 to 4). The simplified hazard consequence/probability matrix was then used to rank the risks, giving a final score that was calculated by multiplying the likelihood of occurrence and expected harm. For further clarification, a definition of terms, the rationale for judgement, and assessment categories used are included in Appendix B.

Table 5. Risk matrix used to assess each hazard based on the likelihood of occurrence and spread of harm.

	Likelihood of occurrence			
Expected harm	Low	Moderate	High	Severe
Low	1	2	3	4
Moderate	2	4	6	8
High	3	6	9	12
Severe	4	8	12	16

The likelihood of occurrence and expected harm for each hazard for each settlement type in Delhi was based on a review of the academic literature (Appendix C). In particular, this included literature and datasets on:

- *Environmental exposure risk*; which includes evidence of outdoor environmental quality; indoor environmental quality; the level of infrastructure and services; and other related datasets;
- *Housing conditions/modifiers*; which considered risks in relation to the identified settlement types drawing on evidence of housing quality;
- *Health evidence*; which included relevant health data (recorded deaths in NCT of Delhi), EM-DAT data for India on mortality due to disasters (extreme heat and cold, fires, explosions, and collapse) and other relevant health studies.

Based on this evidence, all authors separately judged the likelihood of occurrence and expected harm as low, moderate, high or severe. These judgments were then compiled by taking the most common (mode) judgement (of the all the individual assessments) for the likelihood and expected harm, these were then used to calculate the final hazard rating. As the analysis method is largely subjective, combining the individual responses accounts for the variation between the authors' ratings, this helps to improve the objectivity and rigour of the assessment. Mode, median, maximum and minimum hazard ratings results are provided in Appendix C for each hazard as a measure of the variability in 'expert opinion'.

Results

Variation in household energy use and CO_2 emissions

The highest energy use was estimated for the planned dwellings, mainly due to the high penetration of A/C (Table 6). Planned settlements dwellings were estimated to use between one half to a third more energy than dwellings from other settlement types. The lowest energy use is estimated in JJ clusters, where ownership of cooling appliances is low and space is limited. In planned housing cooling appliances were estimated to account for 44% of energy use, whereas in JJ cluster dwellings this is was found to account for less than 5% of energy use, with the majority of energy is used for cooking. This suggests that all energy needs are likely not be met in the JJ clusters, particular in regards to cooling.

Estimated annual CO_2 emissions (kg) per settlement type (Figure 3) are distributed similarly to energy consumption.

The Economic Survey of Delhi estimates residential electricity sales for 2011–12 to total 10,861GWh (Government of National Capital Territory of Delhi 2013). By scaling up to stock level, based on the distribution of settlement types and methods outlined above, we estimate a total annual consumption of 11,512GWh, an overestimate of 5%. This discrepancy could be due to a combination of simplifications and assumptions for each settlement type, in particular, the likely penetration of cooling appliances; the likelihood that total electricity use is not fully recorded due to illegal connections in JJ clusters; the use of back-up generators during blackouts; and the fact that A/C units might not be used for all hours that external temperatures exceed the specified threshold. The results of the estimated electricity use (i.e. without cooking) can be compared to other studies evaluating energy use in housing in a composite climate of India (Chunekar *et al.*, Ramesh *et al.* 2012a, 2012b, 2013, Global Buildings Performance Network (GBPN) 2014, Praseeda *et al*. 2016, Mastrucci and Rao 2017). We find that the spread of results is broadly in line with our estimates (Figure 4). A sensitivity analysis of input parameters for the planned dwellings highlights power rating of A/C (R^2 = 0.49) and hours of use (R^2 = 0.33) are the most significant parameters for annual electricity use.

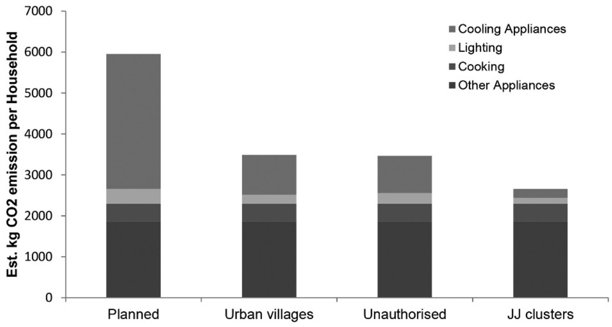

Figure 3. Estimated kg CO_2 emissions per household by settlement type.

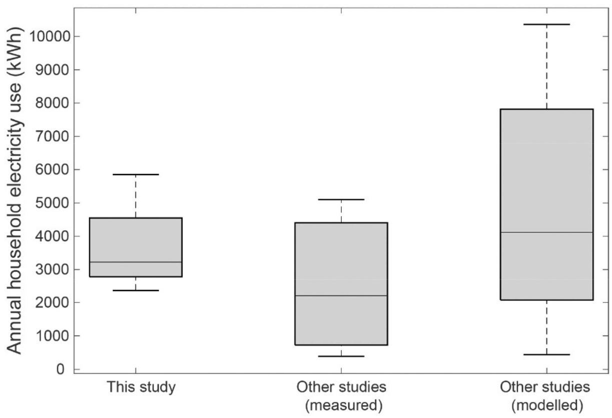

Figure 4. Comparison of electrical energy use estimates with other studies in literature in composite climate.

Variation in housing health risks

The estimated hazard rankings for the different settlement types in Delhi can be seen below (Table 7). The scientific literature and datasets which were used by the authors to estimate the hazard risks and likelihoods are detailed in Appendix B. The final rankings were generated by taking the mode response for both likelihood of occurrence and the expected harm from the individual assessments. The completed risk analysis can now be used to prioritise which hazards require action first.

Particulate matter, heat and cold hazards were assessed to be the largest risks across all four categories of settlement, while vector-borne disease and water supply were also estimated to present significant risks to those in low-income JJ cluster settlements. Structural collapse, fire, overcrowding and, damp and mould hazards were estimated to be moderate

Table 6. Annual energy use by end-use (and percentages) by settlement type.

Energy use (kWh)		Settlement type			
Fuel type	End-use	Planned	Urban villages	Unauthorised	JJ clusters
LPG	Cooking	2028 (26%)	2028 (39%)	2028 (39%)	2028 (46%)
Electricity	Lighting	387 (5%)	234 (4%)	277 (5%)	153 (3%)
	Cooling appliances	3493 (44%)	1033 (20%)	963 (18%)	233 (5%)
	Other appliances	1971 (25%)	1971 (37%)	1971 (38%)	1971 (45%)
Total energy use		7879	5266	5239	4385

Table 7. Estimated household health hazard risks final rating ($S_{O,H}$), with red denoting highest risk hazards and green lowest risk hazards (with modal responses of Low, Medium, High and Severe for the likelihood of occurrence, O, and expected harm, H, noted in subscript).

	Hazard	Settlement type			
		Planned	Urban villages	Unauthorised	JJ Clusters
Physiological requirements: Hygrothermal conditions, pollutants					
1	Damp & mould	$4_{M,M}$	$6_{H,M}$	$4_{M,M}$	$6_{H,M}$
2	Heat	$6_{M,H}$	$9_{H,H}$	$6_{M,H}$	$12_{S,H}$
3	Cold	$6_{M,H}$	$9_{H,H}$	$6_{M,H}$	$9_{H,H}$
4	Particulate matter	$9_{H,H}$	$9_{H,H}$	$9_{H,H}$	$16_{S,S}$
5	Asbestos	$3_{L,H}$	$3_{L,H}$	$3_{L,H}$	$6_{M,H}$
6	Biocides	$2_{L,M}$	$2_{L,M}$	$2_{L,M}$	$2_{L,M}$
7	CO and combustion products	$4_{M,M}$	$4_{M,M}$	$4_{M,M}$	$4_{M,M}$
8	Uncombusted LPG	$2_{L,M}$	$2_{L,M}$	$2_{L,M}$	$2_{L,M}$
9	Lead	$2_{L,M}$	$2_{L,M}$	$4_{M,M}$	$4_{M,M}$
10	Radon	$3_{L,H}$	$3_{L,H}$	$3_{L,H}$	$3_{L,H}$
11	VOCs	$4_{M,M}$	$1_{L,L}$	$1_{L,L}$	$1_{L,L}$
Psychological impacts: Space, security, light & noise					
12	Overcrowding	$2_{L,M}$	$6_{H,M}$	$6_{H,M}$	$6_{H,M}$
13	Entry by intruders	$2_{L,M}$	$2_{L,M}$	$2_{L,M}$	$2_{L,M}$
14	Inadequate lighting	$1_{L,L}$	$2_{M,L}$	$2_{M,L}$	$3_{H,L}$
15	Noise	$2_{L,M}$	$4_{M,M}$	$4_{M,M}$	$6_{H,M}$
Infections: Hygiene, sanitation & water supply					
16	Vector-borne disease	$2_{L,M}$	$6_{M,H}$	$6_{M,H}$	$9_{H,H}$
17	Domestic hygiene	$2_{L,M}$	$6_{H,M}$	$4_{M,M}$	$6_{H,M}$
18	Food safety	$2_{L,M}$	$4_{M,M}$	$4_{M,M}$	$6_{H,M}$
19	Personal hygiene, sanitation and drainage	$2_{L,M}$	$6_{H,M}$	$4_{M,M}$	$6_{H,M}$
20	Water supply	$2_{L,M}$	$6_{H,M}$	$6_{H,M}$	$9_{H,H}$
Accidents: Falls, electric shocks, fires, burns & scalds, collisions, cuts & strains					
21	Falls baths	$1_{L,L}$	$1_{L,L}$	$1_{L,L}$	$1_{L,L}$
22	Falls level surfaces	$1_{L,L}$	$2_{M,L}$	$2_{M,L}$	$2_{M,L}$
23	Falls on stairs	$3_{L,H}$	$4_{M,M}$	$6_{M,H}$	$6_{M,H}$
24	Falls between levels	$2_{L,M}$	$6_{M,H}$	$3_{L,H}$	$4_{M,M}$
25	Electrical shocks	$2_{L,M}$	$4_{M,M}$	$4_{M,M}$	$6_{H,M}$
26	Fire	$3_{L,H}$	$6_{M,H}$	$3_{L,H}$	$6_{M,H}$
27	Flames, hot surfaces	$2_{L,M}$	$4_{M,M}$	$4_{M,M}$	$6_{H,M}$
28	Collision, and entrapment	$2_{L,M}$	$2_{L,M}$	$2_{L,M}$	$2_{L,M}$
29	Explosions	$4_{L,S}$	$4_{L,S}$	$4_{L,S}$	$4_{L,S}$
30	Position and operability of amenities	$1_{L,L}$	$1_{L,L}$	$1_{L,L}$	$1_{L,L}$
31	Structural collapse and falling elements	$3_{L,H}$	$6_{M,H}$	$3_{L,H}$	$6_{M,H}$

risks across all settlements. JJ clusters were estimated to be the most 'at risk' settlement type, followed by urban villages and then unauthorised colonies. Planned settlements are likely to have high-quality dwellings and better access to services and infrastructure, hence providing the lowest risk environments. This variation in health risks across the settlement types presents is likely to cause a disproportional health burden on the low-income groups in Delhi.

Discussion

This paper set out to provide an assessment of energy use and health risks across Delhi's housing stock. The stock was divided into different settlement types, with data from a range of sources reviewed to estimate energy use characteristics and health risks across the settlement types.

Priorities across settlement types

Our assessments indicate significant variation in energy use and health risks between the distinct settlement types found in Delhi. Planned dwellings were estimated to have a much greater consumption of energy in comparison to other settlement types, driven primarily by A/C usage. Taking an average occupancy of 5 across all settlement types gives 1170, 648, 642 and 471kWh/per person for planned, urban village, unauthorised and JJ cluster dwellings respectively, which illustrates that occupants in planned dwellings use almost use twice as much energy person compared to occupants from other settlement types. In urban/rural villages and unauthorised colonies, energy consumption was relatively low and poor indoor environmental conditions were the largest concern. Interventions should aim to improve indoor conditions but not significantly increase energy use. In the informal JJ clusters, strategies should focus on reducing a multitude of health hazards and improving dwelling quality as well as access to infrastructure, services and appliances. Given that the majority of energy use was from cooling appliances and household appliance (TVs and fridges), interventions should focus on energy efficiency for these appliances as well as passive cooling alternatives.

Largest risks to health were found to be hygrothermal conditions (temperature and humidity) and air quality in all settlement types, hazards which could be reduced through better housing design and interventions to modify dwelling performance. Although housing quality has a significant impact on health risks, these are compounded further by levels of household income. For example; in the formally planned dwellings, the high penetration of A/C is likely to reduce exposure to high temperatures but then results in costly energy use, whereas in JJ clusters the poor dwellings and limited access to cooling appliances heighten health risks. This results in a huge disparity in energy use between settlement types, and thus the socio-economic development potential of populations living in those settlements. The strategies in each settlement will differ significantly and interventions will need to appropriately reflect the socio-economic status of each settlement type.

Opportunities to intervene in the planned dwellings are likely to be less restricted compared with the other settlement types, where interventions are limited by the crowded surroundings, dwelling size and financial capacity of the households. Policies will need to reflect current development mechanisms. In urban villages, strategies should focus on maintaining the quality of dwellings, as current regulations that do not restrict development have led to space partitioning and the reduction in ventilation and natural lighting. Interventions in unauthorised colonies can be incorporated in directives as unauthorised colonies become further regularised. In JJ clusters, interventions must be low cost (or heavily subsidised), easy to implement and employ local skills and resources. In general, policies could include incentivised payback periods from energy savings, such as those used in high-income countries, subsidises for materials and efficient appliances, improved housing guidelines and specialised support for homeowners, architects, designers, planners, and the DDA who are a major provider of new housing.

Limitations and implications for future research

This paper represents an initial investigation into the energy use and health risks in housing for the case of Delhi, where there is little previous work or supporting data. Data limitations restrict the level of assessment detail and the accuracy of the results. While it was possible to aggregate the housing stock into four broad categories and describe general characteristics, it is not possible to breakdown the housing further into a set of archetypes and describe in detail their features, which would aid a more accurate estimate of energy use and health hazards. Similarly, energy use data, such as details of occupancy behaviour and appliance use, is restricted to only a couple of studies with limited scope. Additional data collection on housing characteristics in each settlement type is needed and surveys capturing appliance ownership, use and occupancy would provide a more accurate description of energy use across households. Our estimates at a stock level ignore any variation in appliance ownership; for example, we assume 100% penetration of air conditioning across the planned settlements, which is likely to be an oversimplification. It is recommended that national and state-wide surveys, such as the NSS, collect further data on household geometry, the composition of construction materials (beyond material type), and details on ventilation provision and detailed household energy use. This would enable the development of archetypes to establish a stock model that is representative of the housing in Delhi. Without this information, it is only possible to develop broad conclusions. Dukkipati et al. (2014) also recommend more appropriately designed surveys to increase data availability on energy use in India (Dukkipati *et al.* 2014).

Our modelled energy results were broadly in line with previous studies. However, these studies often take idealised or simulated cases, which may not reflect actual use. For example, Ramesh et al. (2012a, 2013) assume heating below 18°C and cooling above 25°C, which is not in line thresholds from thermal comfort studies (Ramesh *et al.* 2012a, 2013) and Mastrucci and Rao (2017) consider the energy required for 'decent' living to meet comfort needs (Mastrucci and Rao 2017). Studies with measured data do not clearly define appliance ownership or their usage, thus making it difficult to compare directly (Praseeda *et al.* 2016). Comparing the energy end-use in the planned dwelling with studies that include space cooling suggest similar trends with the highest energy use from cooling appliances, however, these studies do not consider other appliances such as TV and fridges

(Mastrucci and Rao 2017) or do not provide adequate details of what other appliances were considered so direct comparisons are not possible (Ramesh *et al.* 2012a, 2013). More work is needed to assess actual energy use and interventions that help to protect for health across all housing groups to develop a better understanding of energy consumption and develop appropriate interventions. Furthermore, typically studies report metrics of energy use per unit floor area, which is useful highlighting efficiency in building performance but this is not appropriate for dwellings with vast differences in energy uses and floor area, and may provide misleading results.[1] New metrics that demonstrate the disparities in energy use between households, look beyond building performance and highlight energy use gaps in regards to health risks are vital to pinpoint where interventions should be targeted.

The methods used to assess the energy and health hazards across the settlement types are based on the best available data and expert opinion. Energy use estimates currently do not consider building performance, and variations in occupant behaviour and patterns, this would require in-depth data collection to develop these on a stock level. More sophisticated methods, such as building physics modelling, could provide better predictions of energy consumption as well as indoor environmental quality (hygrothermal conditions and exposure to pollutants). Health impact models could provide estimates of morbidity and mortality based on exposure-response functions. The level of data required for such methods is currently unavailable and significant further research is needed to gather this information. More work in this area is crucial to support effective policy to improve health and sustainability across housing stock in Delhi. Some consideration of the sensitivity and uncertainty in the applied methods is provided. The assessment of health hazards is carried out individually by the authors (variation of the response is provided in Appendix C) and then combined for the formulation of a final ranking, which helps to improve the objectivity of the analysis. A sensitivity analysis for energy use was performed for the planned archetype to assess the most influential parameter. This helped to identify where further detailed data is required as well as evaluate the variability of the overall results, however, further detailed surveying is required to provide the bounds of the parameters and to provide realistic estimates of the uncertainties.

Further data gathering work, the employment of more sophisticated methods and sensitivity analysis to assess variability in results will help to provide a more accurate assessment of health and energy in Delhi housing. However, this paper offers a starting point to focus on further research and helps identify missing data gaps. This assessment is vital in paving the way for more research and detailed investigation of the connections between housing, health and energy. Similar work could be carried out for other locations, as a first step, to raise the agenda of housing as potential means to improve health and sustainable and support progress towards the SDGs.

Conclusions

We developed a framework for the assessment of housing energy use and health risks in low-income settings. The framework employed existing data sets and literature to assess the health risks and energy use across Delhi's housing stock. The framework included the characterisation of the housing stock into archetypes, in this case, by settlement type, and then the assessment of these archetypes in regards to energy use and health risks, drawing on methods from the Built Environment and Public Health.

Despite limitations in data availability, our results show that energy use is nearly two times higher per occupant in planned dwellings compared to non-planned dwellings, as a result of higher ownership of A/C units. Health risks varied considerably across settlement types as a result of variations in the quality of housing, and the ability of occupants to modify their indoor environment. JJ clusters are most likely to be at a higher risk from a wide range of adverse health impacts compared to other settlement types. The greatest health risks, across all settlement types, were assessed to be from exposure to particulate matter, heat, and cold. We highlight the vital need for more data on this topic to enhance understanding of household energy use and health risks, which will help provide a more accurate understanding as well as support further research evaluating interventions.

This work forms a critical first step and can be used to develop guidelines for improving housing, helping to support pathways to an equitable, healthy, sustainable city. Further research should now be carried out to assess levels of exposure to the identified hazards and understand detailed energy use behaviour, as well as to assess intervention performance and trade-offs before implementation. The approach developed could be applied to other locations in India, South Asia and beyond to understand key priorities and interventions strategies that differ with varying housing and environmental risks.

Notes

1. For example, if we assume average floor areas of 80, 40, 60 and 12 m^2 for planned, urban village, unauthorised and JJ cluster dwellings respectively the annual energy use per unit area become 73, 81, 54, and 196kWh/m^2.

This suggests that the JJ clusters are least efficient, however, due to the very small floor area, this is a misleading result.
2. http://www.icrp.org/

Acknowledgments

Expert advice on Delhi housing was received from: Dr Renu Khosla and Siddharth Pandey, from the Centre for Urban and Regional Excellence, India; Swati Janu from microHomeSolutions, Delhi, and Anuj Komar Suni from the School of Planning and Architecture, Delhi.

The authors involved in this work were supported by multiple funding sources. We would like to acknowledge funding from the Engineering and Physical Sciences Research Council (EPSRC) for a Doctoral Training Grant (DTG), the European Union Seventh Framework Programme FP7/2007-2013 under grant agreement no. 265325 ("PURGE"), the UCL Chadwick Trust and the Wellcome Trust funded *'Complex Urban Systems for Sustainability and Health'* (CUSSH) project - grant reference number 209387/Z/17/Z

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the European Union Seventh Framework Programme FP7/2007-2013 [265325]; Engineering and Physical Science Research Council [Doctural Training Grant]; UCL Chadwick Trust [Travelling Fellowship]; Wellcome Trust [209387/Z/17/Z].

Notes on contributors

The authors that have contributed to this manuscript are part of a long-term collaboration (15 years+) between University College London (built environment) and the London School of Hygiene and Tropical Medicine (epidemiology), which has sought to understand the complex relationship between the built environment and human well-being. Through such collaborative research, we have developed a highly productive, multi-skilled team which has sought innovation and stakeholder participation in responding to the world's urban health challenges. This collaboration has helped to articulate the multiple underpinning connections and opportunities for healthy sustainable development.

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Appendices

Appendix A. Sensitivity analysis of energy use variables for the planned settlement archetype

A sensitivity analysis was conducted to understand the impact of input variables on energy use. This was carried out for the planned settlement archetype, which is most likely to use air conditioning. The input variables for power rating and hours of appliance use for each end-use were assumed to follow a normal distribution described by the mean and standard deviation. The mean for each variable was taken as the reported value in the literature, as described earlier in the paper. To account for the variation of each input, the standard deviation was calculated for each appliance from a range of ±20% the mean value. This was selected to account for a potentially wide variation in hours of use and appliance power ratings. Data is not currently available to describe the variation more accurately. The values used to describe each variable are presented in Table A1.

The probability distribution functions of each input variable were then used to generate a random sample to replicate the input variations expected. A sample size of 500 was used as this was deemed large enough so that sample mean does not change by more than 2%, as similar to carried out elsewhere (Das *et al.* 2014). This was done by generating a random number and then using the inverse cumulative distribution function to convert the generated random values into the domain of the input variables. The calculation for energy use was then completed for each permutation of the sample inputs.

To assess the effect of each parameter on the output, correlation-based and regression-based methods were used to measure the strength of the relationship between input and output variables. Pearson's Product Moment Correlation Coefficient was used to measure the strength of linear correlation between each input and output variable. R^2 coefficients were also calculated to assess the proportion of the variance that is predictable from the input variable. The coefficients for each variable are provided in Table A1.

Table A1. Sensitivity analysis input distribution and coefficients for energy use variables.

End-use		Input distribution		Sensitivity analysis method	
Type	Appliance	Mean	Standard deviation	Pearson Coefficient	R^2
Power rating (Watts)					
Lighting	Bulb	60	9.8	0.077	0.0059
	Tube	55	9.0	−0.017	0.00029
Other appliances	TV	120	19.6	0.018	0.00031
	Fridge	200	32.7	0.44	0.20
Cooling appliance	Fan	60	9.8	0.069	0.0047
	AC	1750	285.8	0.70	0.49
Hours of use (hours)					
Lighting	Bulb	5	0.8	0.013	0.00017
	Tube	2	0.3	−0.0094	0.000088
Other appliances	TV	5	0.8	0.077	0.0059
Cooling appliance (living room)	Fans	2881	470.5	0.12	0.015
	A/C	1450	236.8	0.58	0.33
Cooling appliance (bedroom)	Fans	999	163.1	0.020	0.00039
	A/C	140	22.9	0.10	0.010

Appendix B.

The following terms and descriptions were used by the authors to complete the health hazard risk analysis.
Definitions of terms:

- *Occurrence*: This is an event or period of time exposing an individual to a hazard.
- *Likelihood*: The probability of an occurrence that could cause harm and for this work it is to be assessed as the probability of an occurrence over a typical year.
- *Harm*: An adverse physical or mental effect on the health of a person, both permanent and temporary.
- *Expected harm*: The expected possible harm outcome, which could result from an occurrence.

Judging the likelihood of occurrence and expected harm:
For each given hazard the *Likelihood of occurrence* is assessed in regards to;

(i) the average likelihood of the hazard exposure (outdoor conditions, expected indoor conditions etc.)
(ii) the housing conditions/modifiers which may increase or reduce the likelihood of occurrence

and the *Expected harm* is assessed in regards to;

(i) the expected health effect (as described in the UKHHSRS) and health evidence for Delhi/India
(ii) the housing/settlement type conditions/modifiers or population demographics in given settlement type with may increase or mitigate the severity of the outcomes

Assessment categories:
Likelihood of occurrence is categorized as:

- *Low*: chance of occurrence is low and not expected to occur over an annual period
- *Moderate*: chance of occurrence is likely and expected to occur at least once during an annual period
- *High*: chance occurrence is highly likely and expected to occur more than once or over several days during an annual period
- *Severe*: chance occurrence is extremely likely and expected to occur for the majority of the annual period

Expected harm is categorized as:

- *Low*: no or limited harm to health expected (such as broken finger; slight concussion; moderate cuts to face or body; regular coughs or colds)
- *Moderate*: moderate harm to health expected (such as: hypertension; sleep disturbance; allergy; gastro-enteritis; diarrhoea; vomiting . . .)
- *High*: high harm to health expected (such as: asthma, respiratory diseases, lead poisoning, loss of hand or foot, serious burns . . .)
- *Severe*: severe harm to health expected (such as: death, lung cancer, permanent paralysis, permanent loss of consciousness; 80% burn injuries . . .)

Appendix C

Table C1 details the evidence used to generate the estimated likelihood of occurrence and spread of harm based on an assessment of exposure risk, housing modifiers/conditions and available health evidence. The ratings based on the metric developed in section 2.3.1 are also included. The mode (Mo), median (Md), maximum (Mx) and minimum (Mn) values from the individual responses are detailed here for each entry as a measure of the variability in '*expert opinion*'.

Table C1. Exposure risk, housing modifiers/conditions and available health evidence used to estimate the likelihood of harm and expected harm.

					Risk rating per settlement				
Hazard type	Health effects	Exposure risk	Housing modifiers/conditions	Health evidence	Type	Mo	Md	Mx	Mn
Physiological requirements: Hygrothermal conditions, pollutants									
Damp & mould	Asthma, allergic symptoms	- Outdoor RH can increase up to 80% in Delhi during the monsoon season. - Measurements during the monsoon season in apartments in Hyderabad, which has a warm and humid climate, found an indoor RH of approximately 55% (Indraganti 2011), which is close to the 60% risk level for the UK above which of damp and mould growth becomes significant (Department For Communities and Local Government 2006). - The research found high-exposure to fungi for Children in Delhi homes, with highest levels in winter months (Sharma *et al*. 2011).	- Lack of purpose-provided ventilation in both urban/rural villages and in JJ settlements may lead to higher indoor RH in these dwellings due to an inability to remove moisture produced from indoor activities. - Rising damp through poorly constructed dwellings, particularly at risks are low-income dwellings built directly on the ground.	– 2.12% of recorded deaths in the NCT of Delhi from bronchitis and asthma (Government of National Capital Territory of Delhi 2012). - High fungal counts were connected with a higher prevalence of skin sensitization and to respiratory allergies in Delhi Children (Sharma *et al*. 2011).	Planned Urban villages Unauthorised JJ clusters	4 6 4 6	4 6 4 6	6 6 8 9	1 1 2 2
Heat	Cardiovascular stain (stroke), dehydration, respiratory conditions, genitourinary diseases	- Outdoor temperature up to 47°C in Delhi during the summer months. - Indoor temperatures measured in the warm and humid climate regions of India range between 30–39°C during the summer months (Indraganti 2011, Singh *et al*. 2010, Hegde 2010, Dili *et al*. 2010).	- Limited penetration of air conditioning and limited purpose provided natural ventilation, high occupant density, and a lack of climate-sensitive design features in the self-built JJ cluster structures (Mitchell 2010, TERI 2007). - Modifications such as partitioning of structures into multi-unit dwellings in urban/rural villages could lead to overheating in the summer due to a combination of overcrowding and reduced cross-ventilation potential (Kumar Soni 2011). - Planned dwellings are likely to have access to air conditioning with top floor flats shown to be most reliant on A/C use in an observational study carried out in apartments in Hyderabad (Indraganti 2011).	- Heatwave mortality has been increasing (Akhtar 2007) with the highest mortality burden in the poorest states (Kumar 1998). - In Delhi, 3.9% increase in mortality for each degree increase above mean daily temperature 29°C (lags of 0–1 days) (McMichael *et al*. 2008). - EM-DAT database lists 25 heatwaves recorded between 1953 to 2015, resulting in 11,926 deaths across India (Guha-Sapir *et al.*)	Planned Urban villages Unauthorised JJ clusters	6 6 6 12	6 6 9 12	6 9 12 12	2 6 6 9
Cold	Cardio-respiratory illness (including heart attack, stroke, upper and lower respiratory tract infection)	- Minimum outdoor temperatures in winter have been recorded to be 0°C. - Indoor temperatures measured in the warm and humid climate regions of India fell below 19°C during the winter months (Indraganti 2011, Singh *et al*. 2010, Hegde 2010, Dili *et al*. 2010).	- Little evidence of the use of heating systems. - Leaky buildings are unable to control heat loss.	– 2.12% of recorded deaths in the NCT of Delhi from bronchitis and asthma, 1.54% from pneumonia, 0.17% from influenza (Government of National Capital Territory of Delhi 2012). - In Delhi, 3.9% increase in mortality for each degree increase below mean daily temperature 19°C (lags of 0–1 days) (McMichael *et al*. 2008). - EM-DAT database lists 29 cold waves recorded between 1961 to 2015, resulting in 5268 deaths across India and 2 occurrences of severe winter conditions with 320 deaths (Guha-Sapir *et al*.).	Planned Urban villages Unauthorised JJ clusters	6 9 6 9	6 6 6 9	6 9 9 9	1 2 4 4

(*Continued*)

Table C1. (Continued).

Hazard type	Health effects	Exposure risk	Housing modifiers/conditions	Health evidence	Risk rating per settlement: Type	Mo	Md	Mx	Mn
Particulate matter (indoor and outdoor)	Cardiopulmonary disease, lung cancer, asthma. other	- Monthly mean indoor concentrations of PM (from indoor and outdoor sources combined) were found to vary between 56–106 μg/m^3 and 152–201 μg/m3 for PM2.5 and PM10 respectively in two Delhi dwellings (Khillare *et al*. 2004). - A study in 14 residential dwellings in neighbouring Agra found a six-month (between October and March) mean of 135–173 μg/m3 for PM2.5 (Massey *et al*. 2009). These concentrations are far higher than values in outdoor air quality guidance provided by the WHO (WHO 2010) for PM2.5 (maximum annual mean of 10 μg/m3 and 24-hour mean of 25 μg/m3) and PM10 (maximum annual mean of 20 μg/m3 and 24-hour mean of 50 μg/m3). among men and low-income groups (Rani *et al*. 2003). - Indoor sources from cooking. Lighting and heating can also contribute to PM levels.	- Poor-quality structures with very permeable envelopes in urban/rural villages and in JJ settlements put occupants most at risk. - Tighter dwellings and those utilising air-conditioning systems where windows remain closed, such as in the planned settlements, will inhibit the ingress of outdoor pollutants. - 20% of occupants, mainly in JJ clusters, do not have separate kitchens (Government of India 2011), and most dwellings do not have ventilation systems for effective removal of pollutants during cooking times (e.g. through a chimney or an extract fan). - Smoking indoors significantly influences indoor PM levels (Slezakova *et al*. 2009), and smoking rates in India are high (30% of those aged 15 or higher), especially among men and low-income groups (Rani *et al*. 2003).	- Smith estimated the total annual number of premature deaths from indoor air pollution among children below the age of five and adult women is between 400,000 and 550,000 in India (Smith 2000). - 2.12% of recorded deaths from bronchitis and asthma, 6.16% from cancer, 11.21% from heart diseases and heart attacks in the NCT of Delhi (Government of National Capital Territory of Delhi 2012). - SPM levels found to be significant to asthma prevalence amongst children in Delhi households (Kumar *et al*. 2015). - Self-reported health problems as result from indoor air pollution included acute respiratory infections (p-value < 0.001), throat, eye and skin infections (p-value = 0.02), asthma (0.005)	Planned	12	6	12	2
					Urban villages	12	9	12	4
					Unauthorised	9	12	16	9
					JJ clusters	16	16	16	9
Asbestos	Pleural and lung cancer, mesothelioma, asbestosis	- Up to 11% of dwellings in Delhi (Government of India 2011) use asbestos sheets as the predominant material of the roof. If these materials are damaged in any way, they release fibres that are dangerous for health.	- The use of asbestos sheets is most likely in the low-income JJ clusters settlements, where roofing materials are more diverse (Government of National Capital Territory of Delhi 2009).	6.16% recorded deaths from cancer in the NCT of Delhi (Government of National Capital Territory of Delhi 2012).	Planned	3	3	4	1
					Urban villages	1	3	6	1
					Unauthorised	3	3	12	1
					JJ clusters	6	6	16	1
Biocides	Dependent on biocide	*Insufficient data*	*Insufficient data*	*Insufficient data*	Planned	2	2	2	1
					Urban villages	2	2	2	1
					Unauthorised	2	2	4	1
					JJ clusters	2	2	4	1
CO and combustion products (indoor and outdoor) (NOx, NO2 SO2)	Headaches, nausea, damage of airway linings, bronchitis, death	- Indoor concentrations of CO, SO_2, NO_x, and NO_2 measured in neighbouring Agra were found to be below maximum values given in standards produced by India's Central Pollution Control Board (Lawrence *et al*. 2005). - Almost all dwellings in Delhi use LPG, oil, and solid fuels containing carbon for cooking and 0.7% of dwellings use kerosene, other oil, or 'any other' type of fuel for lighting (Government of India 2011). These fuels are sources of PM, NO2, SO2, and CO in the case of incomplete combustion.	– 20% of occupants, mainly in JJ clusters, do not have separate kitchens (Government of India 2011), and most dwellings do not have ventilation systems for effective removal of pollutants during cooking times (e.g. through a chimney or an extract fan).	2.12% of recorded deaths from bronchitis and asthma in the NCT of Delhi (Government of National Capital Territory of Delhi 2012) - NO2 and SO2 found insignificant to asthma prevalence amongst children in Delhi households (Kumar *et al*. 2015).	Planned	4	3	4	1
					Urban villages	4	4	6	1
					Unauthorised	4	4	9	2
					JJ clusters	4	6	16	2
Uncombusted LPG	Asphyxiation	- The use of LPG also presents a risk as it may escape uncombusted into a dwelling due to defects in the installation or appliance.	- Uncombusted LPG could be	*Insufficient data*	Planned	2	3	4	1
					Urban villages	4	3	4	1
					Unauthorised	2	2	9	1
					JJ clusters	2	3	9	1

(*Continued*)

Table C1. (Continued).

Hazard type	Health effects	Exposure risk	Housing modifiers/conditions	Health evidence	Risk rating per settlement: Type	Mo	Md	Mx	Mn
Lead	Neural development and other effects	- Pb elements found in the characterization of ambient $PM_{2.5}$ (Khillare *et al.* 2004, Pant *et al.* 2015), with maximum concentrations up to 2.51 µg/m^3 in a pollution hotspot (Pant *et al.* 2015) - Indoor/outdoor ratios of Pb concentration found to be 0.91–0.97 for two sites in Delhi (Khillare *et al.* 2004), with higher indoor concentrations correlated to road proximity (Kumar 2001).	*Refer to housing modifiers for particulate matter*	*Insufficient data*	Planned Urban villages Unauthorised JJ clusters	2 4 2 4	2 2 2 4	4 4 6 6	1 1 2 2
Radon	Lung cancer	- One study found indoor radon levels to be below an action level of 200 Bq/m3 (based on recommendations in from the International Commission on Radiological Protection[2]) in Delhi (College 2012),	- Ventilation will further impact radon levels, more research is needed to fully assess this issue across a range of dwelling types.	6.16% recorded deaths from cancer in the NCT of Delhi (Government of National Capital Territory of Delhi 2012)	Planned Urban villages Unauthorised JJ clusters	3 3 3 3	3 3 3 3	4 4 6 6	1 1 2 2
VOCs	Allergic reactions, headaches, nausea, drowsiness	- High concentrations of volatile organic compounds (VOCs) in ambient air found in Delhi (Srivastava and Majumdar 2010).	- Volatile Organic Compounds (VOCs) may be found in a variety of materials in the home, with newly built dwellings most likely to be most affected, due to the higher emission rates of VOCs in any new materials such as carpet and paint. - For exposure outdoor refer to housing modifiers for particulate matter	*Insufficient data*	Planned Urban villages Unauthorised JJ clusters	2 2 2 2	2 2 2 2	4 2 2 2	2 1 1 1
Psychological impacts: Space, security, light & noise									
Overcrowding	Increased heart rate and irritability. Increased hygiene risks, accidents, and contagious disease	- Delhi dwellings are at severe risk of overcrowding with a most common occupancy of 6–8 people (26%, (Government of India 2011)) combined with most commonly only one room (32%, (Government of India 2011)).	- Overcrowding has been reported in both the urban/rural villages and JJ cluster settlements (Ishtiyaq and Kumar 2011, Mitchell 2010).	- Overcrowding self-reported to have significant effect on: other common diseases (including headache, nausea, fever and vomiting) (p-value = 0.05); acute respiratory conditions (p-value <0.001); asthma (p-value = 0.03) and tuberculosis (p-value <0.001).	Planned Urban villages Unauthorised JJ clusters	2 6 6 6	2 6 6 8	4 9 9 9	1 2 4 6
Entry by intruders	Stress, injuries	- In 2012, there were 1715 recorded burglaries, up by 20% on the previous year; however, this number appears to fairly low compared to the number of households in Delhi. We assume it likely that many crimes go unrecorded, and there is a high risk of burglary in Delhi households, which could lead to anxiety or injury, in the case of aggregated burglary, to occupants	*Insufficient data*	*Insufficient data*	Planned Urban villages Unauthorised JJ clusters	2 2 2 4	2 2 2 4	2 6 4 6	2 1 1 1
Inadequate lighting	Depression, eye strain	- Inadequate lighting is likely to be an issue, especially during hot periods where curtains are kept drawn to keep the heat out. At times of power cuts and low voltage, lighting levels may fluctuate.	- Studies in an urban village noted inadequate daylight levels and reliance on artificial lighting (Kumar Soni 2011).	*Insufficient data*	Planned Urban villages Unauthorised JJ clusters	1 2 2 3	1 2 2 3	2 6 6 6	1 1 2 2

(*Continued*)

Table C1. (Continued).

Hazard type	Health effects	Exposure risk	Housing modifiers/conditions	Health evidence	Risk rating per settlement: Type	Mo	Md	Mx	Mn
Noise	Irritability, sleep disturbance, headache	- Noise is also likely to be an issue due to overcrowding, high population, dense housing infrastructure, and a high volume of traffic.	*Insufficient data*	A study relating noise pollution to self-reported human health conditions in Delhi (Firdaus and Ahmad 2010) in both a high-density area and a low-density area found a range of adverse health effects including nausea, rise in blood pressure, and depression as a result of factors including vehicles, generators, and household industries.	Planned Urban villages Unauthorised JJ clusters	2 4 4 6	2 4 4 4	4 6 6 6	1 2 1 3
Infections: Hygiene, sanitation & water supply									
Vector-borne disease	Malaria, Dengue fever, Japan	- Vector-borne disease is infections transmitted by the bite of infected arthropod species, such as mosquitoes, ticks, triatomine bugs, sandflies, and blackflies. In India, these risks include: Malaria, Dengue, Lymphatic Filariasis, Kala-azar, Japanese Encephalitis and Chikungunya	- Uncontrollable ventilation, over-occupancy, and inadequate sanitation systems in JJ clusters and urban/rural village dwellings make them particularly vulnerable to the spread of vector-borne diseases (VBDs). – Transmission by direct contact with an infected individual or contaminated surface could be exacerbated in overcrowded dwellings. -Airborne pathogens would be strongly influenced by overcrowding and ventilation rate, with a possible dependence on indoor air conditions like RH and temperature (Li *et al.* 2007).	- The major VBDs in India and their estimated health burdens in 2008 were; malaria (1,524,939 cases with 935 deaths), dengue (12,561 cases with 80 deaths), chikungunya (2,461–95,091 cases), filariasis (26,702 cases), Japanese encephalitis (3,839 cases with 684 deaths) and visceral leishmaniasis (33,234 with 146 deaths) (Dhiman *et al.* 2010), although, apart from dengue, these are more common in rural than urban areas. - 0.30% deaths recorded due to malaria (Government of National Capital Territory of Delhi 2012).	Planned Urban villages Unauthorised JJ clusters	4 6 4 9	3 6 6 9	6 9 9 12	2 4 4 6
Domestic hygiene, pests, refuse	Gastrointestinal disease, asthma, allergic reactions	- Waste collection in Delhi is inadequate; it is reported that around 30% municipal solid waste (MSW) is left uncollected on the street or in small open dumps, and where collected MSW is dumped in uncontrollable open landfill causing a risk to both environment and human health (Talyan *et al.* 2008). Waste can cause pest infestations, which can then cause allergic reactions or carry infectious diseases, further heightening health risks.	- Planned and unauthorised housing tend to have better-managed surroundings or are situated in gated grounds, lowering the contamination potential of some solid waste and some pests, such as feral dogs. - Urban/rural villages and JJ clusters often share street access and surrounding areas can be littered with waste and home to many pests.	– 0.02% of recorded deaths in NCT of Delhi from Rabies, 0.03% Diphtheria, 2.77% tetanus (Government of National Capital Territory of Delhi 2012).	Planned Urban villages Unauthorised JJ clusters	4 6 4 6	2 6 4 6	4 12 4 12	1 2 2 4
Food safety	Food poisoning, gastro-intestinal disease,	- Could be caused by contaminated food or inadequate storage of food. 56% of households are reported to have ownership of a refrigerator (N. S. S. O.-M. of S. & P. I. Government of India 2010b).	- JJ clusters are likely to be most at risk of food contamination due to the overcrowded dwelling with inappropriate storage space or poor hygiene from multi-use surfaces. Ownership of refrigerators lowest among low-income groups (N. S. S. O.-M. of S. & P. I. Government of India 2010b).	– 0.01% recorded deaths from food poisoning, 0.21% dysentery & diarrhoea. 0.03% diphtheria (Government of National Capital Territory of Delhi 2012).	Planned Urban villages Unauthorised JJ clusters	2 4 4 6	2 4 4 6	4 6 4 9	2 2 2 4

(*Continued*)

Table C1. (Continued).

Hazard type	Health effects	Exposure risk	Housing modifiers/conditions	Health evidence	Risk rating per settlement: Type	Mo	Md	Mx	Mn
Personal hygiene, sanitation and drainage	Gastrointestinal disease, skin infections, dysentery	- Sanitation infrastructure in Delhi is limited – 40% of dwellings are reported to have open drains and 7% have no drainage arrangement at all (Government of National Capital Territory of Delhi 2009). - 21% of households are recorded to have no bathroom, with the majority of these households in low-income groups, 63% of households have exclusive use of a latrine, 22% have access to a shared latrine, and 9% have access to public latrines (Government of National Capital Territory of Delhi 2009), further suggesting facilities are limited.	- JJ clusters have the poorest sanitation infrastructure, often with no latrine facilities and substandard open drainage systems. Similarly, urban village infrastructure is haphazard, and as such, drainage and sanitation facilities can be poor (Ishtiyaq and Kumar 2010).	– 0.21% deaths from dysentery & diarrhoea, 0.48% from cholera. 0.03% typhoid, tetanus 2.77%, tuberculosis 3.34%, 0.03% diphtheria (Government of National Capital Territory of Delhi 2012).	Planned	2	2	4	1
					Urban villages	6	4	6	2
					Unauthorised	4	4	9	1
					JJ clusters	9	6	9	4
Water supply	Dehydration, gastro-intestinal disease, legionella	- According to survey data, the majority (84%) of households have access to tap water as a first drinking source, however, only 60% have exclusive use, with nearly 40% relying on shared or community sources (Government of National Capital Territory of Delhi 2009). - Delhi's water supply can be contaminated, with outbreaks of waterborne diseases common (Ministry of Environment and Forests Power Government of India 2001), leading to further risk of illness.	- The low-income groups are most likely to suffer from an inadequate water supply, and JJ clusters are likely to be at the highest risk (Government of National Capital Territory of Delhi 2009).	0.21% dysentery & diarrhoea of all recorded deaths (Government of National Capital Territory of Delhi 2012).	Planned	4	2	4	1
					Urban villages	6	6	9	2
					Unauthorised	6	6	9	1
					JJ clusters	9	9	9	4
Accidents: Falls, electric shocks, fires, burns & scalds, collisions, cuts & strains									
Falls baths	Lacerations, fractures, heart attack, death	- Poor design of bath or mobility of the occupant with heightened hazard.	- Little information about falls in baths but assumed to be the same in all settlement types where baths are available.	0.81% falls and drowning of all recorded deaths (Government of National Capital Territory of Delhi 2012).	Planned				
					Urban villages	1	1	2	1
					Unauthorised	1	2	6	1
					JJ clusters	1	2	6	1
Falls level surfaces	Lacerations, fractures, heart attack, death	- Level surfaces badly finished with large open drains causing heightened hazards.	- Likely to be the case in informally constructed rural/urban villages and JJ clusters.	0.81% falls and drowning of all recorded deaths (Government of National Capital Territory of Delhi 2012).	Planned	1	2	6	1
					Urban villages	2	2	6	1
					Unauthorised	4	3	9	1
					JJ clusters	2	2	9	2
Falls on stairs	Lacerations, fractures, heart attack, death	- Poorly designed stairs and stairs without hand-rails and barriers likely to heighten hazards.	- Likely to be greater in JJ clusters and urban/villages where stairs are often narrow and built on the outside of dwellings, heightening risks if falls occur.	0.81% falls and drowning of all recorded deaths (Government of National Capital Territory of Delhi 2012).	Planned	2	3	9	2
					Urban villages	3	3	4	1
					Unauthorised	4	4	8	1
					JJ clusters	2	3	6	2
Falls between levels	Lacerations, fractures, heart attack, death	- Poorly designed housing or inadequate provision/quality of barriers/rails.	- Dwellings are self-built and often open-fronted denoting a possibility of risk of falling between levels.	0.81% falls and drowning of all recorded deaths (Government of National Capital Territory of Delhi 2012).	Planned	6	6	12	2
					Urban villages	2	3	6	1
					Unauthorised	8	4	8	2
					JJ clusters	4	4	9	1

(*Continued*)

Table C1. (Continued).

Hazard type	Health effects	Exposure risk	Housing modifiers/conditions	Health evidence	Risk rating per settlement: Type	Mo	Md	Mx	Mn
Electrical shocks	Disruption of normal heartbeat/ respiratory muscles, burns, death	- The risk from electrical shocks could arise from unsuitable and badly-installed electrical fittings.	- More likely in low-income households such as JJ clusters, where domestic wiring is temporary or fixed to walls rather than in conduit casing with adequate protection (Government of National Capital Territory of Delhi 2009).	1.36% deaths from accidental burns (Government of National Capital Territory of Delhi 2012).	Planned	6	6	12	2
					Urban villages	3	3	4	2
					Unauthorised	6	6	6	2
					JJ clusters	4	4	12	2
Fire	Burns, death	- Risk of fire could also result from the burning of fuels for cooking, lighting or heating in all settlements.	- In tightly packed JJ clusters or urban/rural villages, the risk of the fire spreading is higher.-	– 1.36% deaths from accidental burns (Government of National Capital Territory of Delhi 2012). - EM-DAT database lists 29 fire occurrences between 1978 to 2015, resulting in 1655 deaths and 50,090 people affected across India (Guha-Sapir *et al.*).	Planned	6	6	12	2
					Urban villages	3	3	4	1
					Unauthorised	6	6	12	2
					JJ clusters	3	4	12	3
Flames, hot surfaces	Burns, death	- The risk for burns from flames and hot surfaces due to cooking, heating or lighting.	- Risks could be higher in cramped dwellings, where the occurrence of accidents are likely to be higher. - 64.9% of all burn admissions were from families living in a single room dwelling unit and 34.3% of admissions from families having two rooms in the dwelling unit and floor level cooking resulted in the majority of accidents.	– 1.36% deaths from accidental burns. Burn deaths could also be a result of septicaemia 4.79% (Government of National Capital Territory of Delhi 2012). - In the Lok Nayak Hospital during 01/01/09 – 31/05/10, 731 out of 991 burn ward patients (73.7%) were flame burns (kerosene, LPG, petrol, coal etc.), 95% in the home. - 56.5% of LPG burn patients were discharged, 33.3% patients expired. 45.3% of kerosene burns discharged, 50.6% expired.	Planned	6	6	12	4
					Urban villages	2	2	4	2
					Unauthorised	4	4	6	2
					JJ clusters	4	4	6	2
Collision, and entrapment	Injuries, fractures, death	- Poor design of openings such as windows/doors and other features.	*Insufficient data*	0.02% deaths from other accidents (Government of National Capital Territory of Delhi 2012).	Planned	6	6	9	4
					Urban villages	2	2	3	1
					Unauthorised	2	2	4	1
					JJ clusters	2	2	3	1
Explosions	Injuries, fractures, death	- Use of canisters for LPG use could risk explosions.	*Insufficient data*	- EM-DAT database lists 10 non-industrial explosions between 1990 to 2015, resulting in 301 deaths across India (Guha-Sapir *et al.*).	Planned	2	2	4	1
					Urban villages	4	4	4	3
					Unauthorised	4	4	6	3
					JJ clusters	4	4	6	3
Position and operability of amenities	Strain and sprain injuries	- Poor design leading to physical strain associated with functional space and other features at dwellings.	*Insufficient data*	*Insufficient data*	Planned	4	4	6	3
					Urban villages	1	1	2	1
					Unauthorised	1	1	2	1
					JJ clusters	1	1	2	1
Structural collapse and falling elements	Injuries, fractures, death	- Poor structural quality causing whole-dwelling collapse, or of an element or a part of the fabric being displaced or falling. - The area is at risk from earthquakes as such dwelling should have an appropriate structure.	- The risk from structural collapse and dilapidation is likely to be higher in both urban/rural villages where there is a lack of maintenance and JJ settlements where structures are often self-built without formal standards (Ishtiyaq and Kumar 2011, Mitchell 2010).	- EM-DAT database lists 43 non-industrial collapse occurrences between 1967 to 2015, resulting in 2941 deaths and 150,000 people affected across India (Guha-Sapir *et al.*).	Planned	1	1	2	1
					Urban villages	3	3	4	1
					Unauthorised	6	6	12	4
					JJ clusters	6	6	12	3