Environment International 69 (2014) 9–17

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

The impact of flood and post-flood cleaning on airborne microbiological and particle contamination in residential houses

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ARTICLE INFO

Article history:
Received 22 January 2014
Accepted 2 April 2014
Available online xxxx

Keywords:
Indoor air
Particle number
PM_{10}
Fungi
Bacteria
Indoor dust

ABSTRACT

In January 2011, Brisbane, Australia, experienced a major river flooding event. We aimed to investigate its effects on air quality and assess the role of prompt cleaning activities in reducing the airborne exposure risk. A comprehensive, multi-parameter indoor and outdoor measurement campaign was conducted in 41 residential houses, 2 and 6 months after the flood. The median indoor air concentrations of supermicrometer particle number (PN), PM_{10}, fungi and bacteria 2 months after the flood were comparable to those previously measured in Brisbane. These were 2.88 p cm^{-3}, 15 μg m^{-3}, 804 cfu m^{-3} and 177 cfu m^{-3} for flood-affected houses (AFH), and 2.74 p cm^{-3}, 15 μg m^{-3}, 547 cfu m^{-3} and 167 cfu m^{-3} for non-affected houses (NFH), respectively. The I/O (indoor/outdoor) ratios of these pollutants were 1.08, 1.38, 0.74 and 1.76 for AFH and 1.03, 1.32, 0.83 and 2.17 for NFH, respectively. The average of total elements (together with transition metals) in indoor dust was 2296 ± 1328 μg m^{-2} for AFH and 1454 ± 678 μg m^{-2} for NFH, respectively. In general, the differences between AFH and NFH were not statistically significant, implying the absence of a measureable effect on air quality from the flood. We postulate that this was due to the very swift and effective cleaning of the flooded houses by 60,000 volunteers. Among the various cleaning methods, the use of both detergent and bleach was the most efficient at controlling indoor bacteria. All cleaning methods were equally effective for indoor fungi. This study provides quantitative evidence of the significant impact of immediate post-flood cleaning on mitigating the effects of flooding on indoor bioaerosol contamination and other pollutants.

1. Introduction

Floods are one of the most common natural disasters and significant flooding events have often resulted in increased morbidity and mortality throughout the world (Ahern et al., 2005; Alderman et al., 2012; Du et al., 2010). Based on the Fifth Assessment Report (AR5) of the United Nations Intergovernmental Panel on Climate Change (2013), extreme precipitation events over most of the mid-latitude land masses and over wet tropical regions will very likely become more intense and more frequent by the end of this century. It implies that major flooding is becoming more frequent and greater in magnitude as the global climate continues to change (Taylor et al., 2011). Therefore, the environmental and public health risks associated with major flooding events are projected to increase in the future.

Flooded areas can become a source and reservoir for pathogens which can impact the health of the residents through various transmission pathways (Taylor et al., 2011). Damp and flooded dwellings can support microbial growth, including mold, bacteria, and protozoa, as well as persistence of flood-borne microorganisms (Taylor et al., 2013), one of which is aerosolization of part or all of the micro-organisms into the indoor air. Exposure to fungal contamination can lead to infectious disease and other health effects which can impact on the respiratory system, skin and eyes. Adverse health effects can be categorized as infections, allergic or hypersensitivity reactions, or toxic irritant reactions (Metts, 2008). However, the role of floods in this process is still not well quantified (Hsu et al., 2011).

Laboratory-based examination of the aerosolization of culturable and total fungi, (1-3)-b-D glucan and endotoxins from eight flood-affected floors and bedding material samples collected from New Orleans homes following Hurricane Katrina was conducted by Adhikari et al. (2009). Their results indicated that significantly higher levels of these contaminants were observed in the flood-affected materials compared to other studies conducted in urban homes. At the same time, the levels of culturable and total fungi found in these materials were slightly lower than those previously reported for moldy buildings. Molds and mycotoxins in indoor dust samples after the same event

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http://dx.doi.org/10.1016/j.envint.2014.04.001
0160-4120/

were also analyzed by Bloom et al. (2009). They reported that the most commonly found mold taxa were *Aspergillus*, *Cladosporium* and *Penicillium*.

Increased levels of airborne indoor microbes (bioaerosols) after major flooding events have been reported in a number of studies (Adhikari et al., 2009; Chew et al., 2006; Fabian et al., 2005; Hoppe et al., 2012; Hsu et al., 2011; Khan and Wilson, 2003; Rao et al., 2007; Ross et al., 2000; Schwab et al., 2007; Solomon et al., 2006). The average indoor and outdoor spore concentration levels varied significantly from study to study and from region to region. In addition to different climatic regions, and sampling methodology, one explanation for this large variation in concentration may also be the different response times and methods used to clean-up after flood. However, there is very limited information available on these parameters in previous studies. Chew et al. (2006) conducted a study to characterize airborne mold and endotoxins throughout all phases (before, during and after) the cleanup process in three houses in New Orleans, which sustained between 0.3 and 1.8 m of flood damage from Hurricanes Katrina and Rita. They reported that after the intervention, which included disposing of damaged furnishings and drywall, cleaning surfaces, drying the remaining structure and treatment with a biostatic agent, the levels of mold and endotoxins were generally lower than pre-intervention levels. Recently, Hoppe et al. (2012) showed that proper post-flood remediation led to improved air quality and lower exposures among residents living in flooded homes.

In January 2011, about 22,000 Brisbane homes and 7600 businesses across 94 suburbs experienced major or partial inundation by flood waters from the Brisbane River. After the flood waters had receded, the local authorities organized an immediate and extensive clean-up operation to remove wet materials and dry out the building structures. To provide a better understanding of the impact of the flood and to test the hypothesis that the cleaning prevented high post flood contaminations, the main objectives of this work were: 1) to assess the effect of flooding on indoor and outdoor PN and PM_{10}, airborne culturable fungi and bacteria concentrations, as well as fungal flora; 2) to investigate the effect of flooding on the concentration of inorganic elements in indoor dust; 3) to analyze the correlations between indoor and outdoor concentrations of the pollutants, as well as indoor inorganic elements in indoor dust; 4) to analyze the role of different cleaning approaches on improving indoor air quality; and 5) to compare the results with the limited data currently available in the literature.

2. Experimental methods

On 13 January 2011, flood waters in the Brisbane River peaked at 4.46 m in Brisbane City and remained elevated until 14 January. The height of water in the flooded houses ranged from 5 to 270 cm. The Brisbane City Council Local Disaster Management Group organized a "Mud Army" of volunteers to assist with clean-up activities immediately after the flood waters receded.

Approximately 23,000 volunteers registered for the first weekend (15–16 January) of the clean-up. They were allocated to sectors and then transported to them by Council bus to assist residents and business owners with debris removal and other cleaning activities. On the second weekend (22–23 January 2012), a large number of parks were cleaned. Council's call for assistance was also answered by many volunteers who did not register. It is estimated that there were between 50,000 and 60,000 volunteers who assisted over the second weekend clean-up activities.

2.1. The sampling sites and houses

Nine residential suburbs of Brisbane located along the banks of the Brisbane River that were affected by the flood were chosen as the measurement sites. Median family income, as reported by the 2011 Census, ranged from AU$52,208 to AU$123,968 for the nine residential suburbs. We delivered almost 600 invitation letters in this area and sent an email invitation via the QUT's media office (with a mailing list size of 2000 recipients). Following this, a total of 41 houses were enrolled, of which 24 were flooded and 17 were not flooded. The latter were used as controls. The houses represented a variety of age, building material and design style. The general house characteristics are described in Table S1 in Supporting information.

2.2. Instrumentation and methodology

2.2.1. Airborne particulate matter

Indoor and outdoor total supermicrometer PN concentrations (from 0.54 to 19.81 μm) were measured by a TSI Model 3312A Ultraviolet Aerodynamic Particle Sizer (UVAPS) (TSI Incorporated, St. Paul, MN, USA), with the time resolution of 20 s.

Two TSI Model 8520 DustTrak aerosol monitors (TSI Incorporated, St. Paul, MN, USA) were used to simultaneously measure indoor and outdoor PM_{10} concentrations. Since the instrument does not measure actual gravimetric values, and in order to obtain values closer to true PM_{10} concentrations, all of the DustTrak data were corrected based on comparison of the DustTrak readings with readings from a TEOM monitor (50 °C R&P 1400a) at QUT.

2.2.2. Bioaerosols

Culturable, viable fungi were collected using a Biotest RCS HIGH FLOW (Biotest Hycon, Art. No. 940210, Ser. No. 30709) centrifugal impact air sampler, for 20 L, 50 L and 100 L air samples, at flow rate of 100 L min^{-1}. Since the concentration of culturable molds in the flooded houses was not known, three sampling volumes were used for the first five houses, in order to ensure that the sufficient amount of material was collected. Rose Bengal agar strips were used for collecting the samples, which were incubated at 28 °C for four days, prior to counting by direct visual inspection. Partial identification as *Penicillium*, *Cladosporium* and *Aspergillus* to a genus level was conducted after seven days incubation. The chosen fungal genera were those frequently occurring indoors, in both Australia and other places in the world (Hargreaves et al., 2003; Jo and Seo, 2005; Mandal and Brandl, 2011; Salonen et al., 2007; Wu et al., 2000). *Aspergillus* and *Penicillium* species were targeted, as they can be toxic at elevated levels, due to their ability to produce mycotoxins. *Cladosporium* has been known to cause several different types of infections, including skin, eye, sinus, and brain infections. *Cladosporium* has also been associated with allergies and asthma (CEN, 2014).

Culturable bacteria were assessed using the same Biotest RCS HIGH FLOW centrifugal impact air samplers, for 100 L samples. Tryptic soy agar strips were used and incubated at 32 °C for three to four days to permit quantification. The results of culturable fungi and bacteria were expressed as colony-forming units per cubic meter of air (cfu m^{-3}).

2.2.3. Dust elemental composition

Dust samples were collected by passive sampling on a 1 m^2 glass panel, which was placed in the living room of each house for one week. The KimWipe tissues used for the dust collection were first pre-cleaned by sonication for 5 min in 3:1 volume to volume mixture of acetone and Milli-Q water (18.2 MΩ cm). After drying the tissues were placed in pre-cleaned sampling tube and weighed. The dust was sampled at each house using the tissue to wipe the dust from the glass and weighed to determine the mass of dust collected. The tissue with the dust was microwave digested in 15 mL of concentrated HNO_3 for 15 min at 180 °C. The diluted digest was analyzed by inductively coupled plasma mass spectroscopy (ICP-MS) (Model Agilent 7500ce) according to the method described in Lim et al (2006). The concentrations of 24 elements, including: Li, Be, Na, Mg, Al, K, Ca, As, Sr, Ba and Pb, together with the transition metals Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Mo, Cd, Ir and Hg were determined. Prior to each analysis the ICP-MS was auto-tuned and calibrated using standards prepared from TraceCert (Sigma Aldrich) standard solutions. All reported elemental concentrations