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Index analysis and human health risk model application for evaluating ambient air-heavy metal contamination in Chemical Valley Sarnia

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ABSTRACT

The impacts of air emissions as a consequence of industrial activities around communities of human habitation have been extensively reported. This study is the first to assess potential adverse human health effects in the Chemical Valley Sarnia (CVS) area, around the St. Clair River, using health risk models, ecological and pollution indices. Large quantities of particulate matters (PM) are generated from anthropogenic activities, which contain several heavy metals in trace quantities with potentially adverse effects to humans and environmental health. The distribution, and human health impact assessment of trace element concentrations in PM fractions were examined. Elemental concentrations of As, Cd, Cr (VI), Cu, Fe, Mn, Pb, Ni, Zn were determined in the PM size-segregated samples collected from the CVS area between 2014 and 2017. The results showed relatively high concentration of $PM_{<2.5}$ $(87.19 \pm 8.1\left(\frac{mg}{m^3}\right))$ which is approximately 4 times the WHO air quality guidelines. Pb concentration $(143.03 \pm 46.87\ \eta g/m^3)$ was 3.6 times higher than the air quality standards of NAAQS. Cr (VI) showed moderate to considerable contamination ($C_f = 4$) in the CVS while Cr (VI), Pb, and Ni had enrichment factor $E_f < 3$ (minimal), signifying contributions from anthropogenic activities. Pollution load index (P_{Li}) value observed was 1.4 indicating human health risk from the PM, especially for the children in the area. The deposition fluxes ($D\Phi$) showed that PM-bound metals could potentially bypass the head airways and cause damages to the tracheobronchial tree, increasing the human health risks of nephroblastomasis development. The main route of entry for the heavy metal bound PM in humans were observed as through ingestion and inhalation. The highest total excess cancer risks observed for children (6.7×10^{-4}) and adult (1.0×10^{-4}) indicating potential cancer effects. The Incremental Lifetime Cancer Risk (ILCR) increased from Pb < Ni < Cd < Cr (VI) < As. Overall, children are more likely to develop carcinogenic and non-carcinogenic health effects from exposures to elemental concentrations of airborne PM in the study area.

1. Introduction

The challenges in the Anthropocene is primarily about finding a sustainable balance between population growth, energy demand, and socioeconomic activities; and the improved quality of human health (Ji et al., 2012; Olawoyin et al., 2012). The consequence of industrialization is widespread, not limited to just the earth's atmosphere. Humans are chronically affected (directly and indirectly) through exposure to pollutants from industrial processes, such as in areas like the "the chemical valley Sarnia" (CVS), where concentrated industrial activities take place (Kulizhskiy et al., 2014).

This refining complex and chemical processing hub in the CVS have attracted a lot of attention from far and wide due to claims of environmental degradation. Peer reviewed studies investigating the extent of pollution in the local communities, particularly of the Aamjiwnaang First Nation's reserve concluded that accumulated effects of environmental pollution altered the gender population of children born in the communities, affirming that more female children are born than boys by a factor of 2 to 1 due to the parental pollution effect (Mackenzie et al., 2005; Van Larebeke et al., 2008). The data on premature death as a result of smog, released by the Ontario Medical Association (OMA, 2008) in the Lambton County area reported 125 fatalities in 2008. The governments of the United States and Canada have established monitoring systems to track the amount of released chemicals in the

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environment; this information is stored in the public domain Canada's National Pollutant Release inventory of Canada (npRi).

The pollutants released in the CVS area are potentially dangerous to human health, they include; carcinogenic metals, particulate matter (PM), polycyclic aromatic hydrocarbons (PAH), persistent organic pollutants (POPs), volatile and semi-volatile organic (VOCs) (Conference Summary Report, 1999; OEHHA, 2009; Zhao et al., 2013; Olawoyin, 2017). PMs are derived from anthropogenic activities including; mining and mineral processing, industrial processes, combustion activities and vehicular traffic (Monaci et al., 2000). Organic and inorganic pollutants, particularly heavy metals and PAHs, have the tendency of being attached to PM which are later deposited from the atmosphere, on trees, soil, land and water (Speak et al., 2012).

The lethal effects of heavy metals exposure are dependent on several factors such as; the toxicity and concentration of the chemical, exposure time, exposure duration, age and body weight of subject exposed, the human health condition etc (Olawoyin et al., 2012). There has been an increase in reported cases of cancer prevalence especially on the US side of the Chemical Valley, specifically in the St. Clair County of Michigan. The St. Clair County Health Department (SCCHD, 2012) reported occurrences of cancer cases in the St. Clair County area through the Michigan Cancer Registry (MCR).

Wilms tumor (WT) is an uncommon, solid tumor comprising of epithelial, metanephric blastema, and stromal derivatives, formed from immature kidney cells and abnormal tissues growing quickly on the exterior of the kidney and compressing the normal kidney parenchyma, resulting to a condition known as Nephroblastomatosis (Guaragna et al., 2010; da Silva et al., 2011). The period between 1990 and 2009, several people were diagnosed having WT or Nephroblastoma, 63% of which occurred in children of age < 5years (SJCRH, 2014). The occurrence of 72.2% of the WT cases were from 2000 to 2009 in Marine City, with a prevalence rate of approximately 1:500 based on the 2010 population census in the area (SCCHD, 2013). The American Cancer Society identified Nephroblastoma as the 4th most prevalent cancer occurrence in children < 5 years old (Fontham et al., 2009). The specific cause of WT is yet to be identified; some scientific aetiology have suggested the cause to be genetically derived, while others have attributed the cause of WT to be from environmental risk exposures (SJCRH, 2014).

Epidemiological studies have established links between the quality of human health and exposure to PM bound up with elements such as Ag, As, Au, Cd, Cr (VI), Cu, Fe, Hg, Mn, Pb, Ni, Zn etc. (Kukutschova et al., 2011; Pant and Harrison, 2013; Sanderson et al., 2014). Arsenic, Cd, Cr (VI), and Ni are classified as carcinogenic to humans (Group 1), by the International Agency for Research on Cancer (IARC, 2017). These elements are of concern to human health due to their persistence in the environment, bioaccumulation in the food chain, toxicity and carcinogenic tendencies (Olawoyin, 2012). The carcinogenic metals such as; As, Cd, Cr (VI), Pb and Ni are considered to be highly harmful to humans if chronically exposed (EEA, 2013). Particulate matter is classified according to the aerodynamic diameter as; *ultrafine* (< 0.1 µm – $PM_{0.1}$), *fine* (< 2.5 µm – $PM_{2.5}$), *thoracic* (< 10 µm – PM_{10}). Heavy metals are adsorbed on $PM_{0.1}$, $PM_{2.5}$ or PM_{10}, with the finer PM carrying more of the toxic elements. The adsorbed elements and the PM have been observed as risk factors that contribute to the development of lung cancer, cardiopulmonary injuries, systematic inflammation, endothelial injuries, atherosclerosis, other respiratory diseases, neurodevelopmental and neurodegenerative abnormalities (Rao et al., 2014; Bai and Sun, 2016). Considering the mass of PM exposure, the individual contributions of the elements to PM are minute, however, the small amount may be potentially harmful to human health when they accumulate in large quantities. The routes of PM adsorbed elements exposure to humans are through ingestion (*ing*), inhalation (*inh*), and dermal absorption (*dab*), (Olawoyin et al., 2012).

Considering the adverse effects of PM bound toxic elements, in this study, we investigated the impacts of human exposure to metals (trace quantities) present in PM, and their accumulation in the air of the CVS area. The various pollution indices used (contamination factor (C_f), enrichment factor (E_f), pollution load index (P_{Li}), degree of contamination (C_d), and the target hazard quotient (TH_Q)) provided the risk estimation and potential correlation with the incidence of the cancer cluster in the CVS area. The goal of this study was to assess the impact of industrial processes contributing to environmental pollution with the potential to exacerbate the development of nephroblastomasis in the CVS area.

2. Materials and methods

2.1. Physical characterization of the study area

2.1.1. Area under investigation

Canada like many other industrialized nations hosts industries with variable activities in and around the country. Majority of the industries in the country (about 40%) are located in an estimated area of 308 mi^2 (which is about the size of Kansas City (Missouri) and slightly bigger than New York City (New York)) called the city of Sarnia. The area around Sarnia along the St. Clair River is typified as the "Chemical Valley Sarnia – CVS" due to the presence of many chemical processing plants, and is the largest city in Lambton County and on Lake Huron. In 2011, the population in the area was estimated as 89,555, having a 0.9% population increase from the previous 5 years (Stat. CA, 2011). Sarnia is situated at an international border between the State of Michigan (at Port Huron) in the US and Canada. Its location is between the Upper Great Lakes and the Lower Great Lakes, at the point through which Lake Huron meanders into the St. Clair River, which is one of a dozen other areas around the Great Lakes of potential concern, identified for possible environmental health assessments, due to the prevalent pollution regimes in the area (Health Canada, 2000).

The climatic condition in the Lake St. Clair area is mostly influenced by the location of the lake, which reduces the effects of Great Lakes weather patterns relative to the westerly winds and the prevailing wind blows southwesterly that has an average speed of 10 mph (Great Lakes Commission, n.d.). Similarly, "lake" effects from Lake Huron are also experienced from the northerly winds. The late fall and early winter months are marked by cloudiness and the temperature are modified in the summer months due to the breezes from Lake St. Clair (Great Lakes Commission, n.d.). The region rarely experiences lengthy periods of hot, humid weather in the summer or extreme cold during the winter. Summer precipitations occur mostly as afternoon showers with moderate thunderstorms. Average evaporation from May to October exceeds the average precipitation by more than 80%. In the winter, the snowfall average is about 34.4 in. (Great Lakes Commission, n.d.).

The southern and eastern and southern parts of the St. Clair County are covered by several glacial lake sub-stages of the Pleistocene age Wisconsin glacial stage (Brown, 1963). These glacial sediments are mainly composed of clay amalgamated with discontinuous lenses of glacio- and glacio-lacustrine gravels and sands (Gillespie et al., 2008). The sediments occur in the lower portions of the sediments and the average thickness of the glacial deposits ranges from 50 to 160 ft. Typical rock types in te area include, sandstone, shale, and hematite (USGS, 1988). Regional water flows in the direction towards the St. Clair River or the Black River, however, groundwater can be obtained from the basal areas of the discontinuous lenses (USGS, 1988; Gillespie and Dumouchelle, 1989). The St. Clair River forms an international boundary with Canada with 240 sq. miles at the north and has the largest coastal delta in the Great Lakes. It flows into Lake Huron to the north and into the Detroit River from the southwest which flows into Lake Erie in the south (Conference Summary Report, 1999) (Fig. 1).

The bedrock topography was reported to be influenced by glacial erosions due to lithographic differences from differential weathering. It is primarily flat with minor folds of gradational dipping towards the east of St. Clair River (Brown, 1963; Dorr, 1981, Gillespie et al., 1989).