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# Assessing mercury pollution in Amazon River tributaries using a Bayesian Network approach

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ABSTRACT

Mercury pollution of water bodies exerts significant human and ecosystem health impacts due to high toxicity. Relatively high levels of mercury have been detected in the Amazon River and its tributaries and associated lakes. The study employed a Bayesian Network approach to investigate the contribution from geogenic sources to mercury pollution of lakes in the Madeira River basin, which is the largest tributary of the Amazon River. It was found that the source indicators of naturally occurring mercury have both, positive and negative relationships with mercury in lake sediments. Although the positive relationships indicated the influence of geological and soil formations, the negative relationships implied that the use of mercury amalgam for gold extraction in artisanal and small-scale mining (ASM), which is the primary anthropogenic source of mercury, also contribute to mercury in Amazon tributaries. This was further evident as mercury concentrations in lake sediments were found to be significantly higher than those in the surrounding rocks. However, potential anthropogenic mercury was attributed to historical inputs from gold mining due to the recent decline of ASM mining practice in the region.

## 1. Introduction

Amazon, as the world's most biodiverse system of tropical rainforests, is the home to a large number of species of freshwater flora and fauna (Castello et al., 2013; Junk et al., 2007). However, this water environment is subject to significant risks due to the presence of a range of toxicants of natural and anthropogenic origin, and one of the major concerns is mercury (Hg) pollution of Amazon River tributaries. As a highly toxic pollutant, Hg can pose risks to human health once ingested through contaminated fish.

In fact, Amazon waters can be polluted by Hg due to: (1) geogenic factors such as transport of naturally occurring Hg in soil into waterways and atmospheric emissions from Andes volcanic eruptions (Bonotto and Vergotti, 2015); and (2) use of Hg amalgam for gold extraction from ore in artisanal and small-scale mining (ASM) (Pacyna et al., 2010; UNEP_Chemicals_Branch, 2008). However, it is important to note that ASM gold mining has decreased in intensity over the past years (Bastos et al., 2006). Therefore, it can be hypothesised that the current Hg content in river waters and sediments could be sourced from naturally occurring Hg as well as historical inputs from previous ASM gold mining.

The investigation discussed in this paper characterised the potential degradation of Amazon ecosystem due to geogenic Hg inputs, and thereby identified any potential contributions from anthropogenic sources of Hg. This is due to the practical constraints in the Amazon region to collect reliable data on ASM gold mining activities, as a consequence of the wilderness, difficulty in terrestrial access and zones of conflicts with indigenous people, among others. The study adopted Bayesian Networks (BNs), which is a novel approach in the context of environmental systems modelling. BNs are a graphical modelling approach embedded with straightforward interpretability, and has been used for understanding complex environmental systems. Past studies include, prediction of species abundance as a function of habitat characteristics (Howes et al., 2010), assessment of influential factors in the occurrence of cyanobacterial blooms in tropical lakes (Rigosi et al., 2015), modelling the impact of vehicular traffic on the build-up of

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hydrocarbons on urban roads (Li et al., 2017), evaluation of the influence of land use change on urban receiving waters (Wijesiri et al., 2018a), assessment of human health risks in developing countries due to poor urban water quality (Wijesiri et al., 2018b), and comparison of the impact of urbanisation in different geographical regions on stormwater pollution (Wijesiri et al., 2018c).

Further, BNs have emerged as an effective modelling approach as it facilitates the utilisation of expert elicited information and historical data for developing the model structure. It enhances the handling of sparse data and the derivation of scientifically robust inferences (Stefanini, 2008). However, it is also important to note that expert elicitation needs to be performed in a way that it does not lead to inaccurate discretisation of variables (limits the capture of the characteristics of observed data) and derivation of less reliable prior information (Uusitalo, 2007).

Accordingly, the main objective of the current study was to develop a BN model to assess the contribution from geogenic sources to Hg in the sediments of Amazon lakes. The outcomes of the research study are expected to contribute to the formulation of effective planning and management strategies to minimise the impact of Hg, and thereby safeguard the Amazon aquatic ecosystem.

## 2. Materials and methods

### 2.1. Study sites

The study was based in the Madeira River basin located in Rondônia State, Brazil. As shown in Fig. S1 in the Supplementary information, Madeira is the largest of several basins that comprise the system of Amazon rainforests. The sediment sampling sites were located in nine lakes (0.6–5 km in length and 0.3–1.2 km in width) as shown in Fig. 1, and their main features have been detailed in Bonotto and Vergotti (2015). Further, the population in the surrounding area of the lakes varies from 120 inhabitants to 2000 inhabitants. The major economic activities of the population include fishing, agriculture (rice, corn, manioc, banana, coffee, coconut and water melon) and extractive industries (chestnut and açaí).

In addition to sediments from the nine lakes, a total of six rock samples were collected at Teotônio and Santo Antônio waterfalls (Fig. S2 and Table S1 in the Supplementary information). The petrographic, geochemical, and geochronological aspects of the rock formations were characterised by Payolla (1994). The major lithologies consisted of coarse-grained igneous rocks comprising granites, syenites and monzonites.

### 2.2. Sample collection and laboratory analysis

The core sediment samples were collected over a maximum depth range of 20–80 cm from the lake bed by driving a 1 m long and 7 cm diameter PVC tube attached to an iron outliner. Samples were collected approximately in the central area of each lake, and each sample was cut into 5 cm thick slices and transferred into polyethylene bags, stored in iceboxes, and then transported to the laboratory. The maximum depth (and respective number of slices) of core sediments collected at each lake was: Samuel – 20 cm (4); Paca – 25 cm (5); Demarcação – 35 cm (7); Brasileira – 55 cm (11); Conceição – 50 cm (10); Araçá – 80 cm (16); Tucunaré – 65 cm (13); Santa Catarina – 50 cm (10); and Nazaré – 25 cm (5). Quality Assurance and Quality Control procedures were followed during sample handling and storage (Azcue et al., 1994).

The sediment samples collected were analysed for elemental Hg and indicators of geogenic Hg, namely, major oxides ($Al_2O_3$, $Fe_2O_3$, $TiO_2$, SiO2, MgO, CaO, $Na_2O$ and $K_2O$) and organic carbon. The selected oxides are typical parameters analysed to perform geochemical balance of the composition of rocks, soils and sediments (Faure, 1991) and largely influence Hg transport through soil, while organic carbon content indicates the likelihood of forming Hg-organic complexes (Belzile et al., 2008; Brigham et al., 2009; Gu et al., 2011).

To determine the concentration of elemental Hg in lake sediments, the samples were first digested, and then analysed using atomic absorption spectrometry with cold vapour generation by following the Method 7471B (USEPA, 2007). For the rock samples collected, only the elemental Hg was analysed. The rock fragments were initially crushed using jaw crushers in two stages, first, from 5 cm to 1.5 cm size, and then 1.5 cm to 3–5 mm. Subsequently, crushed rock samples were further size reduced to < 400 µm in an oscillating mill and submitted to the same analytical procedure adopted for Hg determination in the lake sediments.

The concentrations of oxides were determined using X-ray Fluorescence (XRF) method as described by Beckhoff et al. (2007). Total Organic Carbon (TOC) in sediments was determined using spectrophotometry as described by Hach (1992).

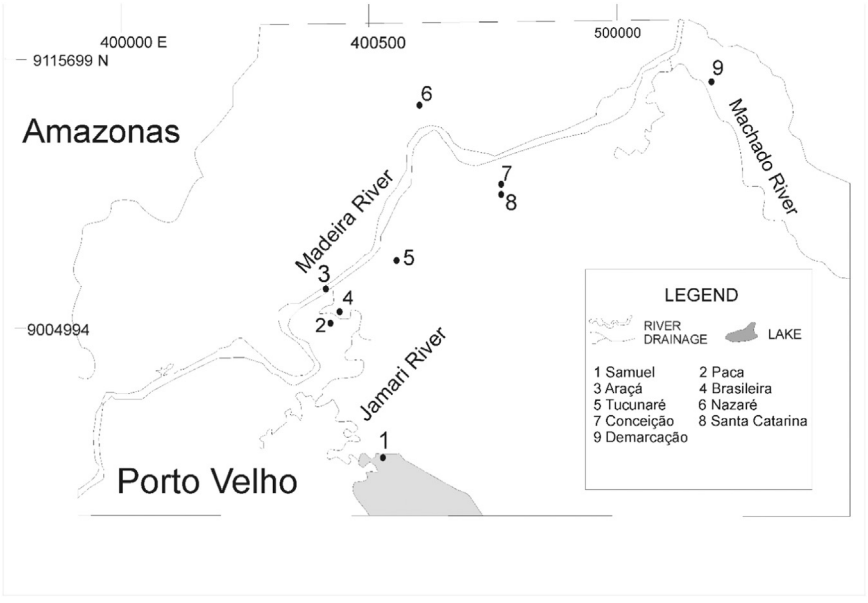


**Fig. 1.** Locations of lakes (adapted from Bonotto and Vergotti, 2015).