

## Article

# Population Attributable Fraction (PAF) of Lung Cancer Mortality in India Due to Groundwater Arsenic Exposure

Ruohan Wu<sup>1</sup> and David A. Polya<sup>2,\*</sup> 

<sup>1</sup> School of Geography and Planning, Sun Yat-Sen University, Guangzhou 510006, China; wurh35@mail.sysu.edu.cn

<sup>2</sup> Department of Earth and Environmental Sciences, School of Natural Sciences, Faculty of Science and Engineering, University of Manchester, Manchester M13 9PL, UK

\* Correspondence: david.polya@manchester.ac.uk

## Highlights

### What are the main findings ?

- Population attributable fraction (PAF) of lung cancer mortality due to groundwater arsenic is modeled.
- The PAF for India is calculated to be 1.4% (95% CI;  $\pm 1.8\%$ ).
- State-level PAFs vary widely, the highest being 12% for Assam and 8% for West Bengal.

### What are the implications of the main findings ?

- Removing groundwater arsenic exposure could reduce lung cancer deaths in India by ~1000/year.
- Groundwater arsenic exposure is a relatively minor risk factor for lung cancer mortality in India.
- Groundwater arsenic is not the main driver of secular increases in lung cancer mortality in India.

## Abstract

Chronic consumption of groundwater arsenic is a well-known risk factor for many cancers, notably lung, bladder, kidney and skin cancers, and is recognized as such in many countries, notably India. Indeed, increasing cancer incidence and mortality in India has been ascribed to such exposure. Notwithstanding this, there has hitherto been a dearth of quantitative data on the magnitude and spatial distribution of groundwater arsenic attributable cancer mortality in India. Here, we combined random forest model-derived data on the spatial distribution of groundwater arsenic in India with India census data on populations and groundwater usage and recently published dose–response relationships to address this knowledge gap through a population attributable fraction (PAF) approach. We show that around 1.4% (95% CI;  $\pm 1.8\%$ ) of all lung cancer mortality in India can plausibly be attributable to exposure to groundwater arsenic. Whilst this is a substantial range of values, it is too small to sensibly indicate any plausibility of the narrative of groundwater arsenic exposure being primarily responsible for the increased cancer incidence and mortality in India over the last few decades. Nevertheless, the modeled spatial distribution of groundwater arsenic exposure PAF of lung cancer mortality in India may inform public policy aimed at reducing environment-related detrimental health outcomes.

**Keywords:** arsenic; groundwater; hazard; exposure; India; lung cancer; dose–response; population attributable fraction (PAF); environment and health



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## 1. Introduction

Arsenic in groundwater utilized for drinking or cooking has long been identified as a major risk to human health with both carcinogenic (e.g., lung, bladder, kidney, skin cancers) [1–7] and non-carcinogenic (e.g., cardiovascular disease) detrimental health outcomes [5,7–11] being important aspects of this. After Bangladesh, India is arguably the country that is most impacted by groundwater arsenic with tens of millions of people exposed [12–14] to groundwater-derived drinking water with arsenic exceeding the WHO provisional guide value of 10 µg/L [15]. It is widely reported that exposure to groundwater arsenic is a major cause of cancer in India [16–18]; indeed, it is further reported or implied [19] that it is responsible for the substantive increased prevalence of many cancers in India at either a national or state level. However, there is a paucity of studies to quantitatively substantiate either of these claims or the extent to which they may be valid, including with respect to different parts of the country.

There are few detailed spatially resolved models of the public health impacts of groundwater arsenic in India. A notable exception is the work of Wu et al. (2021) [20] who determined the spatial distribution of groundwater arsenic attributable cardiovascular disease mortality in India. Wu et al. (2021) [20] used a population attributable fraction (PAF) approach [21], which is readily extended to modeling cancer mortality as an end-point provided that suitable dose–response data were available. Lung cancers are a major group of cancers (i) that cause over 50,000 deaths per year in India [22] and for which there is not only extensive evidence of a causal link of arising mortality with exposure to arsenic via drinking water [23–26] but for which dose–response relationships have recently been published in systematic reviews involving meta-analyses or other studies [25,26] enabling the PAF approach to be extended to these sequelae.

The aim of this study was to provide a detailed spatially resolved quantification of the model population attributable fraction (PAF) of lung mortality in India attributable to direct or indirect ingestion of groundwater arsenic. Calculation of a PAF readily enables quantification of the relative importance of groundwater arsenic exposure and (collectively) other risks to the spatial distribution of lung cancer health burdens in India. The work is intended as a scoping study, the limitations of which are discussed along with suggestions for further work to improve the models.

## 2. Materials and Methods

### 2.1. Overall Approach

Secondary data for (i) the spatial distribution of arsenic in groundwater in India; (ii) the spatial distribution of rural and urban population in India; and (iii) the spatial distribution of groundwater usage for drinking water in India were used to (iv) determine the spatial distribution of the magnitude of human exposure to groundwater arsenic across India and then combined with (v) dose–response relationships between lung cancer mortality and drinking water arsenic concentrations and (vi) theoretical equations for population attributable fractions, to (vii) calculate the spatial distribution of the fraction of lung cancer mortality in India attributable to human exposure to groundwater arsenic. In this section, in turn, are described (i) the theoretical basis and equations utilized in the calculations and (ii) the sources of the secondary data utilized in those equations. Unless otherwise stated, all calculations were carried out in Microsoft® Excel® for Microsoft 365 MSO (Version 2511 Build 16.0.19426.20260) 64-bit.

### 2.2. Theoretical Basis

The population attributable fraction,  $PAF_{h,c,a}$ , for a groundwater contaminant,  $c$ , such as arsenic, to a detrimental health outcome,  $h$ , such as annual lung cancer deaths, in an

administrative area,  $a$ , such as a state or district, is related to the relative risk,  $RR_{h,c}(x)$ , of the detrimental health outcome,  $h$ , due to the contaminant,  $c$ , as a function of the contaminant concentration,  $x$ , and the administrative area population distribution,  $P_{a,c}(x)$ , and counterfactual (adopted reference) population distribution,  $P_{a,c}'(x)$ , with respect to the concentration,  $x$ , of contaminant,  $c$ , by Equation (1) (with  $m$  being the maximum contaminant concentration; modified after [27]):

$$PAF_{h,c,a} = \frac{\int_{x=0}^{x=m} RR_{h,c}(x) P_{a,c}(x) dx - \int_{x=0}^{x=m} RR_{h,c}(x) P_{a,c}'(x) dx}{\int_{x=0}^{x=m} RR_{h,c}(x) P_{a,c}(x) dx} \quad (1)$$

where the population distribution with respect to the contaminant concentration is not known as a continuous distribution but rather discretely with respect to a series of concentration classes or levels and for which  $RR_{h,c,1} = 1$  for the lowest level, then Equation (1) may be simplified to Equation (2) modified after [20,21,28]. Thus, the population attributable fraction,  $PAF_{h,c,a}$ , for a groundwater contaminant,  $c$ , such as arsenic, to a detrimental health outcome,  $h$ , such as annual lung cancer deaths, in an administrative area,  $a$ , such as a country, state or district, can be calculated by Equation (2):

$$PAF_{h,c,a} = \frac{\sum_{\ell=1}^{\ell=n} F_{t,\ell,a} (RR_{h,c,\ell} - 1)}{\sum_{\ell=1}^{\ell=n} F_{t,\ell,a} RR_{h,c,\ell}} \quad (2)$$

where  $F_{t,\ell,a}$  is the fraction of the total administrative area population exposed to groundwater contaminant level,  $\ell$ ;  $n$  is the number of such groundwater contaminant levels; and  $RR_{h,c,\ell}$  is the risk of the detrimental health outcome,  $h$ , at the contaminant exposure level,  $\ell$ , relative to that,  $RR_{h,c,1} = 1$ , for the reference exposure level,  $\ell = 1$ . Implicit assumptions of this approach are that there is no non-zero population attributable fraction of the detrimental health outcome due to the contaminant in the reference exposure level and that  $RR_{h,c,\ell}$  is independent of age, sex, genetic and behavioral characteristics. It is noted that all of  $F$ ,  $RR$  and  $\ell$  may have, indeed likely do have, different values for different contaminants.

In heterogeneous administrative areas, where groundwater usage may be distinctly different between rural ( $r$ ) and urban ( $u$ ) areas, the fraction,  $(F_{t,\ell,a})$ , of the total ( $t$ ) area population exposed to groundwater contaminant level  $\ell$  can be calculated by the following:

$$F_{t,\ell,a} = \frac{(F_{r,\ell,a} \times P_{r,a}) + (F_{u,\ell,a} \times P_{u,a})}{P_{t,a}} \quad (3)$$

where  $P_{t,a}$ ,  $P_{r,a}$  and  $P_{u,a}$  are the total, rural, and urban population respectively of the administrative area,  $a$ , and  $F_{r,\ell,a}$  and  $F_{u,\ell,a}$  are the fractions of households drinking groundwater in rural and urban sub-areas respectively of the administrative area,  $a$ , and calculable by Equations (4) and (5):

$$F_{r,\ell,a} = \frac{A_{l,a}}{A_{t,a}} \times X_{d,gw,r,a} \quad (4)$$

$$F_{u,\ell,a} = \frac{A_{l,a}}{A_{t,a}} \times X_{d,gw,u,a} \quad (5)$$

where  $X_{d,gw,r,a}$  and  $X_{d,gw,u,a}$  are the fraction of the households drinking groundwater in rural and urban areas of a district respectively and  $A_{l,a}/A_{t,a}$  is the fraction of the total area of the administrative area,  $a$ , for which the groundwater contaminant level is  $\ell$ . These equations assume that the mean household occupancies are the same in rural and urban sub-areas within a given administrative area and that there is no difference within the given administrative area,  $a$ , between the fractional distribution of a given groundwater contaminant level,  $\ell$ , of rural and urban areas.

Where groundwater contaminant classification levels are known on a grid of equidimensional pixels or cells, then these data can be converted into  $A_{l,a}/A_{t,a}$  values for each contaminant level and administrative area by Equation (6):

$$\frac{A_{l,a}}{A_{t,a}} = |L_l \cap A_a| / |A_a| \quad (6)$$

where  $|S|$  refers to the number of members of the inscribed set;  $M$  is the set of all grid cells;  $L_\ell$  is the set of all grid cells within  $M$  for which the groundwater contaminant level is  $\ell$  and  $A_a$  is the set of all grid cells within  $M$  for which the centroid is in an administrative area,  $a$ .

It follows that the rural,  $P_{r,\ell,a}$ , urban,  $P_{u,\ell,a}$ , and total,  $P_{t,\ell,a}$ , populations exposed to a groundwater contaminant at a given contaminant level,  $\ell$ , within a given administrative area,  $a$ , may be calculated by the following:

$$P_{r,\ell,a} = F_{r,\ell,a} \times P_{r,a} \quad (7)$$

$$P_{u,\ell,a} = F_{u,\ell,a} \times P_{u,a} \quad (8)$$

$$P_{t,\ell,a} = F_{r,\ell,a} \times P_{d,r} + F_{u,\ell,a} \times P_{u,a} \quad (9)$$

Finally, the total detrimental health outcomes,  $\mathcal{O}_{h,c,a}$ , attributable to a groundwater contaminant,  $c$ , in a given administrative area,  $a$ , can be calculated from the population attributable fraction,  $PAF_{h,c,a}$ , by the following:

$$\mathcal{O}_{h,c,a} = \Omega_{h,a} \cdot PAF_{h,c,a} \quad (10)$$

where  $\Omega_{h,a}$  is the total detrimental health outcomes,  $h$ , irrespective of their cause or risk factors, in the administrative area,  $a$ .

### 2.3. Secondary Data and Data Sources

The district-level distribution of groundwater arsenic concentrations across India was derived from the all-India country-wide 1 km  $\times$  1 km scale machine learning model of Wu et al. (2021) based on secondary groundwater arsenic data compiled between 2005 and 2020 [20]. In brief, ref. [20] followed the random forest approach of Podgorski et al. [13] but with a somewhat updated dataset. Predictive variables included those plausibly related to expert-identified processes leading to elevated groundwater arsenic concentrations [20,29–32]. More details on random forest modeling and justification of it as an effective modeling approach have already been detailed elsewhere [13,20,33–35]. Whilst there are also other machine learning models of groundwater arsenic including India as part of the modeling (e.g., [36,37]) or modeling specific areas of India (e.g., [13,33,38–40]), we preferred, here, the use of the Wu et al. (2021) [20] model because the adequacy of the model at a country scale was specifically demonstrated through cross-validation approaches and because both granular state-level and district-level concentration data were readily available from the novel pseudo-contouring carried out [20] and which enabled the classification of groundwater arsenic concentrations at 1 km  $\times$  1 km scale into 5 levels/classes, viz., level 1: As = 0 to <10  $\mu\text{g/L}$ , level 2: As =  $\geq 10$  to <20  $\mu\text{g/L}$ , level 3: As =  $\geq 20$  to <50  $\mu\text{g/L}$ , level 4: As =  $\geq 50$  to <80  $\mu\text{g/L}$ , and level 5: As =  $\geq 80$   $\mu\text{g/L}$ . These 1 km  $\times$  1 km classifications were then converted into values of  $A_{l,a}/A_{t,a}$  for each class/level for each state or district in India using Equation (6).

Population data, all of total, rural and urban, at all of country, state and district level, were obtained from the India Census of 2011 [41].

Data on groundwater usage as drinking water,  $X_{dgr,r,a}$  and  $X_{dgr,u,a}$ , for rural and urban sub-areas respectively at a district level were obtained from [42], considering hand pump and tubewells/boreholes sources—this corresponds to exposure model 2 of [20] (see Figure 1b of [20] for district-wise groundwater usage as drinking water distribution across

India)—and excludes the following categories of drinking water supply: “tap water from treated source”, “tap water from un-treated source”, “covered well”, “un-covered well”, “spring”, “river/canal”, “tank/pond/lake” and “other sources”. None of the excluded sources correspond unequivocally to likely high arsenic groundwater sources and most correspond to sources, notably treated water and surface or near surface waters, that are generally, albeit not always, expected to be low in arsenic.

Secondary dose–response data for lung cancer mortality and groundwater arsenic concentrations were found by a systematic search of English-language systematic reviews with a meta-analysis published over the period 2015–2025 and indexed by Web of Science (All Collections). The search term combination used was as follows: TITLE = arsenic and “lung cancer” and (“systematic review” or “meta-analysis”) and YEARS = 2015 to 2025; and LANGUAGE = English. Of the two papers [25,26] identified by the search, only one paper [26] explicitly included dose–response data for mortality end-points so we have adopted the dose–response data from [26] as follows. Relative risks,  $RR_{h,c,\ell}$ , for lung cancer mortality were determined for the mid-point concentration of each groundwater arsenic level/class, viz., 5, 15, 35 and 65  $\mu\text{g/L}$  for levels 1, 2, 3 and 4 respectively and, following the approach of [20], 131  $\mu\text{g/L}$  for level 5. Since explicit dose–response data were not available for these specific concentrations, to enable their calculation over the range of 15–131  $\mu\text{g/L}$ , relevant tabulated dose–response data were fitted using unweighted least squares regression to a second-order polynomial fit of the form:

$$RR(x) = \beta_0 + \beta_1 x + \beta_2 x^2 + \varepsilon \quad \text{for } x = 15\text{--}131 \text{ } \mu\text{g/L} \quad (11)$$

with

$$RR(x) = 1.00 \quad \text{for } x = 0\text{--}10 \text{ } \mu\text{g/L} \quad (12)$$

where  $x$  is the value of the concentration of groundwater arsenic expressed in units of  $\mu\text{g/L}$ .

Absolute values of lung cancer mortality for India by state or territory for the years 1980 to 2023 were obtained from [43] data for combined tracheal, bronchus and lung cancers—in tabulating those data, we combine the data for the now separate states of Andhra Pradesh and Telangana; we further note that the comparative rarity of tracheal and bronchus cancers in India means that these combined secondary data more than adequately represent lung cancer mortality data without any unacceptable loss of accuracy for the purposes of this paper.

### 3. Results

#### 3.1. Groundwater Arsenic Hazard and Exposure Distribution

The state-level and district-level distribution of groundwater arsenic across India utilized in this study has previously been tabulated and otherwise presented by Wu et al. (2021) (see their Figure 2e) [20]. Given that, we only briefly summarize here some of the key features of those distributions—notably that relatively high (taken here to be greater than the WHO provisional guide value of 10  $\mu\text{g/L}$  [15]) groundwater arsenic concentrations tend to be more commonly found in the north and north-east parts, notably West Bengal and Assam, of India; and which, coincidentally, tend also to be parts of the country in which hand pumps and tubewells/boreholes are more commonly used for drinking water, particularly in rural areas (for more details, see [20]). The total number of people exposed to high groundwater arsenic is estimated to be around 60 million, a value intermediate between that of Podgorski et al. [13] and Mukherjee et al. (2021) [14], and a value still [20] preferred by us since it is based on a more realistic and granular exposure model than those of the other estimates [13,14]. As noted by [20], the precision of both hazard and exposure data tends to be substantively better at country level and state level

than at district level and for that reason, our further calculations of groundwater arsenic exposure PAF for lung cancer mortality is limited to the country level and state level.

### 3.2. Relative Risks of Lung Cancer Mortality as a Function of Drinking Water Arsenic

The relative risks of lung cancer mortality at the mid-point concentrations of the groundwater arsenic concentration classes/levels utilized in this study are presented in Table 1 together with the best-fit coefficients used to calculate those RR values. The estimated 95% confidence intervals are on the order of  $\pm 30\%$  and for one class/level, the lower bound of the 95% confidence intervals is notably below 1.000.

**Table 1.** Dose–response relationships between lung cancer mortality and arsenic concentration in drinking water. Pooled relative risks (95% CIs) of lung cancer mortality for the median concentration in each arsenic concentration class/level utilized in this relative to the median concentration in the reference class/level of 0–10  $\mu\text{g/L}$ . Calculated from Equation (11) in the text with  $\beta_0 = 9.220 \times 10^{-1}$ ;  $\beta_1 = 1.631 \times 10^{-2}$ ; and  $\beta_2 = -4.293 \times 10^{-5}$ ; (valid over the range 10–131  $\mu\text{g/L}$ ); and Equation (12) in the text, derived by fitting the tabulated data for As > 10  $\mu\text{g/L}$  of [26] to Equation (11);  $R^2 = 0.99$ .

| Groundwater Arsenic Concentration Class/Level Range ( $\mu\text{g/L}$ ) | Groundwater Arsenic Concentration Class Median Concentration ( $\mu\text{g/L}$ ) | Lung Cancer Mortality Relative Risk (95% CI) |
|-------------------------------------------------------------------------|----------------------------------------------------------------------------------|----------------------------------------------|
| [0, 10)                                                                 | 5                                                                                | 1.00 (1.00, 1.00) <sup>1</sup>               |
| (10, 20]                                                                | 15                                                                               | 1.16 (0.81, 1.50) <sup>2</sup>               |
| (20, 50]                                                                | 35                                                                               | 1.44 (1.01, 1.87) <sup>2</sup>               |
| (50, 80]                                                                | 65                                                                               | 1.80 (1.26, 2.34) <sup>2</sup>               |
| [>80]                                                                   | 131                                                                              | 2.32 (1.63, 3.02) <sup>2</sup>               |

Notes: <sup>1</sup> RR is set to unity for the reference class/level. <sup>2</sup> RR 95% CIs calculated from the rounded arithmetic mean ratio (30%) of (upper bound RR-RR)/RR and (RR-lower bound RR)/RR values tabulated by Issanov et al. (2024) [26].

### 3.3. Population Attributable Fraction (PAF) of Lung Cancer Mortality in India Linked to Groundwater Arsenic Exposure

The calculated PAF of lung cancer mortality in India linked to groundwater arsenic exposure for each state and the country as a whole is presented in Table 2.

**Table 2.** Calculated PAF (population attributable fraction) (with 95% CI) of lung cancer mortality in India and Indian states linked to exposure to groundwater arsenic. Estimates of groundwater arsenic exposure attributable lung cancer deaths in 2011 are uncertain values, calculated from the product of PAF (this study) and secondary published lung cancer mortality data [22].

| Administrative Area         | Groundwater Arsenic Exposure Attributable Fraction of Lung Cancer Mortality (95% CI) | Reported Lung Cancer Mortality (2011) <sup>1</sup> | Estimated Groundwater Arsenic Exposure Attributable Lung Cancer Deaths (2011) <sup>2</sup> |
|-----------------------------|--------------------------------------------------------------------------------------|----------------------------------------------------|--------------------------------------------------------------------------------------------|
| Andhra Pradesh <sup>3</sup> | 0.0% (0.0%, 0.0%)                                                                    | 3749                                               | (0)                                                                                        |
| Arunachal Pradesh           | 2.5% (−0.2%, 5.0%)                                                                   | 45                                                 | (1)                                                                                        |
| Assam                       | 12.0% (−3.6%, 23.5%)                                                                 | 1634                                               | (195)                                                                                      |
| Bihar                       | 2.2% (−2.0%, 6.0%)                                                                   | 1010                                               | (22)                                                                                       |
| Chhattisgarh                | 0.0% (0.0%, 0.1%)                                                                    | 753                                                | (0)                                                                                        |
| Goa                         | 0.0% (0.0%, 0.0%)                                                                    | 66                                                 | (0)                                                                                        |
| Gujarat                     | 0.0% (0.0%, 0.0%)                                                                    | 2684                                               | (0)                                                                                        |
| Haryana                     | 1.3% (−1.5%, 3.9%)                                                                   | 1245                                               | (16)                                                                                       |
| Himachal Pradesh            | 0.0% (0.0%, 0.1%)                                                                    | 344                                                | (0)                                                                                        |

Table 2. Cont.

| Administrative Area       | Groundwater Arsenic Exposure Attributable Fraction of Lung Cancer Mortality (95% CI) | Reported Lung Cancer Mortality (2011) <sup>1</sup> | Estimated Groundwater Arsenic Exposure Attributable Lung Cancer Deaths (2011) <sup>2</sup> |
|---------------------------|--------------------------------------------------------------------------------------|----------------------------------------------------|--------------------------------------------------------------------------------------------|
| Jammu and Kashmir         | 0.5% (−0.1%, 1.1%)                                                                   | 836                                                | (5)                                                                                        |
| Jharkhand                 | 0.2% (−0.1%, 0.4%)                                                                   | 512                                                | (1)                                                                                        |
| Karnataka                 | 0.0% (0.0%, 0.0%)                                                                    | 2405                                               | (0)                                                                                        |
| Kerala                    | 0.0% (0.0%, 0.0%)                                                                    | 4087                                               | (1)                                                                                        |
| Madhya Pradesh            | 0.1% (−0.1%, 0.2%)                                                                   | 3279                                               | (2)                                                                                        |
| Maharashtra               | 0.0% (0.0%, 0.0%)                                                                    | 3096                                               | (0)                                                                                        |
| Manipur                   | 0.6% (−0.3%, 1.5%)                                                                   | 230                                                | (1)                                                                                        |
| Meghalaya                 | 0.1% (0.0%, 0.2%)                                                                    | 138                                                | (0)                                                                                        |
| Mizoram                   | 0.3% (−0.1%, 0.7%)                                                                   | 141                                                | (0)                                                                                        |
| Nagaland                  | 0.8% (−0.5%, 2.1%)                                                                   | 59                                                 | (0)                                                                                        |
| Delhi                     | 1.1% (−0.8%, 2.9%)                                                                   | 1163                                               | (13)                                                                                       |
| Odisha                    | 0.4% (−0.4%, 1.2%)                                                                   | 1391                                               | (6)                                                                                        |
| Punjab                    | 2.0% (−1.8%, 5.4%)                                                                   | 1079                                               | (21)                                                                                       |
| Rajasthan                 | 0.0% (0.0%, 0.0%)                                                                    | 1965                                               | (0)                                                                                        |
| Sikkim                    | 0.0% (0.0%, 0.0%)                                                                    | 32                                                 | (0)                                                                                        |
| Tamil Nadu                | 0.0% (0.0%, 0.0%)                                                                    | 4351                                               | (0)                                                                                        |
| Tripura                   | 0.1% (−0.1%, 0.2%)                                                                   | 268                                                | (0)                                                                                        |
| Uttar Pradesh             | 0.5% (−0.4%, 1.4%)                                                                   | 9487                                               | (51)                                                                                       |
| Uttarakhand               | 0.5% (−0.5%, 1.6%)                                                                   | 990                                                | (5)                                                                                        |
| West Bengal               | 7.8% (−0.2%, 14.8%)                                                                  | 6238                                               | (437)                                                                                      |
| <b>INDIA <sup>4</sup></b> | <b>1.4% (−0.5%, 3.2%)</b>                                                            | <b>53,399</b>                                      | <b>(738)</b>                                                                               |

Notes: <sup>1</sup> Absolute numbers of lung cancer death by state from [22] (Institute for Health Metrics and Evaluation. Used with permission. All rights reserved. Terms and conditions: <https://www.healthdata.org/Data-tools-practices/data-practices/ihme-free-charge-non-commercial-user-agreement> accessed on 10 February 2026).; <sup>2</sup> given the uncertainties in reported lung cancer deaths—see [22]; these values are considered rather uncertain; <sup>3</sup> data for Andhra Pradesh are combined data for the states of Andhra Pradesh and Telangana; <sup>4</sup> the relatively small administrative areas of Andaman and Nicobar Islands, Chandigarh, Dadara and Nagar Haveli, Daman and Diu, Lakshadweep and Puducherry have not been included in the analysis due to a lack of relevant data.

For India, the PAF value is 1.4% (95% CI: −0.5%, 3.2%), which represents around 700 groundwater arsenic attributable deaths of the approximately 53,000 reported for 2011 by [22] and around 1000/annum for the current (2026) population if the PAF is assumed to remain constant between 2011 and 2026. Notably, the lower bound of the 95% CI is less than 0.0%—this reflects the magnitude of the 95% CIs for the drinking water arsenic–lung cancer mortality dose–response relationship [22] utilized here (see Table 1)—indeed, whilst there are also imprecisions and inaccuracies associated with the modeling of both groundwater arsenic hazard and human exposure to it [20], the negative PAF 95% CI lower bounds not just for India but for many states indicate that these errors are outweighed by those associated with the utilized dose–response relationship.

There is considerable variation in PAFs from state to state. Whilst for many states, the PAF is less than 1%, indeed close to 0.0%, for a number of states, the PAFs are considerably higher than that—notably for Assam (12.0% (95% CI: −3.6%, 23.5%)); West Bengal (7.8% (95% CI: −0.14%, 14.8%)); Bihar (2.2% (95% CI: −2.0%, 6.0%)) and the Punjab (2.0% (−1.8%, 5.4%)). These elevated values broadly reflect a combination of the known elevated groundwater arsenic concentrations in many parts of those states and the known elevated levels of

groundwater usage for drinking and cooking in many parts of those states, and notably in rural areas.

## 4. Discussion

In this section, limitations of the model and data are briefly discussed before outlining what are some of the implications of the results.

### 4.1. Limitations of the Study

The results presented here are subject to limitations related to both (a) errors and uncertainties in the input data; and (b) errors associated with the model utilized, in particular, the validity of key model assumptions. These are outlined below with respect to each of the hazard, exposure and dose–response models.

There are some important limitations to consider in our usage of these groundwater hazard models, notably (i) process heterogeneity [20,43] means that the weighting of optimal hazard predictor variables in one part of the modeled area may well not be the optimal weighting in other parts of the modeled area, where different processes controlling groundwater arsenic may be important; in particular, the relative importance of the reductive dissolution of arsenic-bearing Fe-O-H phases, oxidation of arsenian iron sulfides and pH-dependent competitive desorption may vary spatially across India (cf. [12,13,16,31,32]); and (ii) the hazard model adopted is a 2D model rather than a more realistic 3D model [13,20] but for which relevant secondary depth-dependent data are less available and for which modeling is more challenging because of the geological, hydrogeological and hydrobiogeochemical complexity of sub-surface aquifer systems in many parts of India [12,13,16,20,39].

With respect to the exposure model utilized, it is recognized that (i) the omission of springs and some shallow wells may give rise to an under-estimation of groundwater arsenic exposures; (iv) the current state of drinking water supplies (in 2026) will be different from those in 2011, not least of all due to groundwater arsenic mitigations implemented by governments and NGOs; (ii) granular consideration of age, gender, body weight and behavioral factors influencing individual water consumption rates has not been considered and, in particular, the spatial distribution of these across various states in India; and (iii) there have been substantial changes in population since 2011.

With respect to the dose–response model utilized, it is recognized that it is based on epidemiological studies not exclusively focused on India (cf. [28]). Further, the dose–response model utilized is agnostic to sex, age, genetics and behavioral characteristics (e.g., smoking, other forms of tobacco usage). Whilst the PAF approach to a large extent mitigates some of these issues, nevertheless, if there are non-zero interaction terms between arsenic exposure [44] and any of these factors AND there is a substantive spatial variation in these factors, then this might lead to systematic biases in the estimation of model PAF values—such biases would be expected to be much more evident at the smaller district level, so we have restricted our reported calculations to state level and country level. Irrespective of synergistic or antagonistic effects, numerical biases may be introduced by not modeling a continuous distribution of arsenic exposures but rather five categorical classes of exposure. Lastly, we note several studies that have questioned the accuracy of dose–response relationships for various sequelae at low to moderate drinking water arsenic concentrations below 100 µg/L, generally claiming lower (if any) demonstrable health impacts at those concentrations [45,46].

Nevertheless, notwithstanding these limitations, the hazard, exposure and dose–response models used here enable a useful first step in the model of groundwater arsenic exposure PAF of lung cancer mortality in India and which may form the theoretical basis for improved estimates in the future.

#### 4.2. Implications

There are several important public health implications of the results of this study. Firstly, although exposure to groundwater arsenic is clearly a contributing factor to the development and mortality arising from lung cancers in India, its importance is much outweighed by other factors. This is a similar finding to that of [27], who found that for France, all of tobacco usage, alcohol consumption, diet, obesity and infections were substantively more important risk factors, albeit for all cancers, not specifically lung cancer, than was arsenic exposure. Notwithstanding the relatively higher groundwater arsenic concentrations in India than in France, the PAFs calculated here nevertheless also point to other factors being considerably more important than arsenic exposure to the overall burden of lung cancer disease. Whilst remediation of high groundwater arsenic-derived drinking water supplies is clearly indicated for other reasons, for the sole purpose of reducing lung cancer burden, it is evident that efforts might be more cost-effectively placed in other directions (e.g., for effective programs aimed at reducing tobacco usage or reducing obesity).

Further, the magnitude of groundwater arsenic exposure as a risk factor for lung cancer mortality is simply too small, 1.4% (95% CI;  $\pm 1.8\%$ ), for this exposure to be a major driver of secular increases in lung cancer incidence and mortality in India. The reported incidence of cancer, including lung cancer, has been increasing by several tens of percent over the last decade and is projected to continue to increase by a similar magnitude over the next decade [43,47,48]—instead, this can be largely ascribed to a combination of (i) an aging population; (ii) improved quality of drinking water supplies, particularly with regard to infectious agents, and improved public health services and systems addressing other causes of mortality; and (iii) improved rates of reporting and detection [47–49]. Other risk factors for lung cancer in India include tobacco usage [50], occupational exposures, outdoor air pollution [51], indoor air pollution (including through the burning of biofuels) and socioeconomic factors.

Lastly, whilst the PAFs calculated here are relatively small at a country scale, there are regions in India, notably Assam and West Bengal, but also further areas, where the combination of the demonstrated or modeling impacts of groundwater arsenic exposure on public health, not just in relation to lung cancer but also to other detrimental health outcomes, such as cardiovascular disease (CVD) [20], still indicates the importance of remediating or providing mitigations in relation to groundwater arsenic hazard.

## 5. Conclusions

This study presents, for the first time, a quantitative hazard–exposure–receptor model that shows that exposure to groundwater arsenic plausibly gives rise to around 1.4% of all lung cancer mortality in India. We note the limitations of the model, including with respect to input data accuracy and representativeness and with respect to model assumptions, particularly in relation to the dose–response model adopted. Lastly, we note that the model is reported here at a country and state level rather than at a district level (for which model uncertainties are inevitably higher) and should not—as is typical of such population-level models—be used to estimate health risks for individuals. We highlight that the model could be used to inform public health policy decisions particularly in relation to the management of detrimental health outcomes arising from the use of groundwater as drinking or cooking water.

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