Systematic review of occurrence and distribution of manganese in drinking water in India and implications for population health

Joyce Liu, Carly Barello, Siddhartha Roy, Michael B. Fisher

Abstract

Objectives: This study seeks to understand manganese occurrence in drinking water in India.

Methods

We searched PubMed, EBSCO Global Health, and Web of Science in December, 2021 and included peer-reviewed studies published after 1969 in English that reported manganese concentrations in drinking water in India (protocol registered with PROSPERO: CRD42024566116). Bias within studies was assessed using methodological quality scores. Regressions and a diagnostic plot were used to assess bias among studies. Results are presented using summary statistics, maps, and estimated populations drinking water exceeding national standards and WHO benchmarks.

Results

Extracted data comprised 6,397 observations in 74 studies spanning 59 districts in 24 states. Manganese concentrations ranged from 0 to 12,797 µg/L and were not associated with season or water supply technology ($p > 0.05$). Overall, 9% of disaggregated data and 21% of aggregated data (95% CI: 9-34%) exceeded the Indian (BIS) national standard for manganese in drinking water (300 µg/L), while 32% of disaggregated data and 58% (40-76%) of aggregated data exceeded the 2022 WHO provisional guideline value of 80 µg/L. Using empirical Bayesian kriging, we estimate nearly 60 million people (95% CI: 45-73m) may be consuming groundwater exceeding BIS standards; over 300 million (281-365m) may be drinking water exceeding WHO provisional guidelines.

Discussion

Limitations in this work include variable study quality, dearth of evidence from some states, and low availability of raw study data. Results indicate that a substantive proportion of India's population may be exposed to manganese in drinking water at levels of potential concern. Such findings could help inform ongoing efforts to achieve universal access to safely managed drinking water for the Indian population.

Funding

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Introduction

Trace metals occur naturally in the environment and can be mobilized through both natural and anthropogenic processes; many have toxic effects at elevated concentrations. Such toxic metals (TMs) include arsenic, cadmium, chromium, lead, and manganese, among others. Arsenic and manganese are geogenic contaminants, meaning that they can contaminate groundwater as a result of natural geochemical processes.[1] Occurrence of geogenic TMs can pose risks to large populations using groundwater as a (primary) source of drinking water or other domestic and agricultural use, particularly in settings and water systems where these hazards may not be routinely monitored and managed.

Manganese is a trace metal that causes health concerns including neurologic issues when consumed at high concentrations.[2] Regulation of and guidelines for allowable manganese concentrations in drinking water vary by context and have evolved over time.[1] The World Heallth Organization (WHO) set a provisional guideline of 400 µg/L in 1958 that was intended to protect against the most vulnerable populations; however, this was discontinued in 2011 because “this health-based value is well above concentrations of manganese normally found in drinking water [and] not considered necessary to derive a formal guideline value.”[3] The WHO has subsequently established a more conservative provisional health-based guideline of 80 µg/L[4]. The US Environmental Protection Agency (EPA) establishes a health advisory level of 300 µg/L, as well as a Secondary Maximum Contaminant Level at 50 µg/L for aesthetic purposes[2]. The Bureau of Indian Standards has also established the permissible limit of manganese in drinking water to be 300 µg/L[5].

India is the world’s largest user of groundwater, and the largest country by population, with a population of 1.4 billion people in 2023.[6] Groundwater in India accounts for as much as 80% of domestic usage.[7] Currently, India is undertaking a national campaign to ensure availability of safe water for all its citizens, in alignment with national strategies as well as international targets under Sustainable Development Goal 6 (SDG 6).[8–10] Characterizing and managing the occurrence of chemical hazards is integral to this effort, but representative monitoring of manganese in drinking water is not currently widespread.[11] Synthesizing available evidence on manganese occurrence into a usable and accessible format can therefore be helpful in ongoing efforts to maximize safely managed drinking water services.

Objectives: This study aims to synthesize, visualize, and quantify available evidence on the distribution of manganese occurrence in groundwater in India through literature review and meta-analysis. The study also estimates the occurrence of manganese in groundwater at levels that exceed applicable benchmark and guideline values, as well as the approximate proportion of India’s population that may be affected. Finally, the study examines geographic and seasonal trends in the distribution of manganese occurrence, as well as associations (if any) with water system type.

Methods

Search Strategy

This work uses data extracted as part of a larger systematic review project focusing on 14 toxic metals (TMs) in low- and middle-income countries (LMICs) as defined by the World Bank's country and lending groupings.[3] This larger review was registered with Prospero (CRD42024566116) and the current study was undertaken using the same protocol, with a more limited geographic and contaminant focus: studies reporting on manganese in drinking water in India. We followed PRISMA guidelines for reporting (see S1: PRISMA Checklist). Briefly, We searched PubMed, EBSCO Global Health, and Web of Science in December, 2021for articles related to toxic metals in drinking water in low- and middle-income countries (see S2: Search Strategy).

Refining search results

A very large number of results was returned, and a machine learning tool was trained and used to identify those results with the highest probability of inclusion, as described in the study protocol (see S3: Study Protocol). Briefly: All search results from the three search engines were screened with a Machine learning algorithm using supervised clustering (DoCTER [ICF, Virginia, USA]) trained to prioritize most relevant results. The first 500 results were manually screened at the title and abstract level and these were used to train the algorithm to rank results by propensity to be included at the title and abstract level (propensity score). The subset of studies with passing propensity scores were then uploaded to Covidence and deduplicated.

Eligibility

Studies were excluded if they were published before 1969 or in a language other than English, contained no primary data, did not quantitatively report concentrations of TMs of interest, were not conducted in an LMIC, or did not report measurements in drinking-water sources or sources likely to be used for drinking (Table 1).

Screening

Each study was independently screened by two reviewers at both the title and abstract stage and at the full-text screening stage. Conflicts were resolved by a third reviewer.

Table 1. Inclusion and exclusion criteria used in study screening

Table 1: Inclusion and exclusion criteria used in study screening. The current work uses a subset of studies (those on manganese in India) identified in a larger systematic review of toxic metals in drinking water in LMICs..

Include	Exclude
1. Based in an LMIC (India*) 2. Provides a quantitative measure of trace metals of interest in water sample 3. Discusses a trace metal of interest (Manganese*). 4. Trace metal appears in a drinking water source (incl. water bottles).	1. Duplicate 2. Non-English Language 3. Study is not based in LMIC (India*), or the setting cannot be determined 4. Does not provide a quantitative measure of a trace metal of interest (Manganese*)

	5. Trace metal (Manganese*) is only measured in food, diet, wastewater, or recreational water source. 6. The trace metal (Manganese*) measure is taken from animals, i.e. animal studies 7. The trace metal (Manganese*) measure is taken from humans, i.e. it is a human health assessment 8. The study is primary focused on the testing of remediation techniques 9. The study is a commentary, review, periodical, or book

*Denotes refinements of criteria used in the larger study that are applicable to the current work

Data Extraction

A total of 74 studies reporting manganese concentrations in drinking water in India met the inclusion criteria and were extracted (by a single team member), yielding 6,397 observations, 172 of which had data reported individually (disaggregated at the single source/sample level).

Data Items

Data were extracted for manganese concentrations in micrograms per liter (µg/L) for studies with disaggregated data and descriptive statistics (mean/median/minimum/maximum/standard deviation) for manganese concentrations in micrograms per liter (µg/L) for studies reporting aggregated data. All results consistent with these outcomes were extracted. Data were also extracted for the following variables: season of sample collection, water system type, subnational location (village/district), state, , geographic coordinates of sampling (where available), and numbers of samples taken. The season of sample collection was determined from the studies stating them; based on the seasons of India and months of data collection reported, if any, temporal relation to monsoon season (before, during, or after) was also included in the data. In India, spring/summer or pre-monsoon roughly lasts from February to June, monsoon season lasts from July to September, autumn or post-monsoon lasts from October to November, and winter lasts from December to January.[12] Similarly, sources of drinking water were recorded.

Dataset Cleaning, Groupings, and Estimation of Missing Parameters

Sources of drinking water were categorized as "improved" or "unimproved" based on the WHO/UNICEF Joint Monitoring Programme (JMP) between the WHO and UNICEF.[13]

Furthermore, water sources labeled by the authors as borehole, bore well, tube well, and handpump were all classified as "boreholes"; sources labeled as lake, pond, dam water, streams, rivers, and backswamp were all classified as "surface water"; unprotected and unspecified wells were grouped together; springs and rainwater were individual groups; all other sources were labeled as "other". Sources with a combination of improved and unimproved systems, e.g.

boreholes with handpumps and dug wells, were categorized in a separate "combined" group and considered unimproved.

Where disaggregated observations were reported, these were used as received with the following exception: for values reported as nondetects, a continuity correction was made by substituting one half the analytical method detection limit for the reported "nondetect" value. If no method detection limit was reported, an indicative method detection limit for a published analytical method (e.g. EPA method or APHA method) using the same type of instrument (e.g. ICP-MS, GF-AAS, etc.) was used (Table S4: Indicative Detection Limits).

Where aggregated observations were reported, studies varied in methods of reporting summary statistics. Most reported some combination of the following: median, average (arithmetic mean), range (minimum and maximum), standard deviation (SD), and number of observations (n). However, several studies did not report all of these parameters. To estimate missing parameters for aggregated observations, we used the following approximation methods where needed. If no mean was reported, we used the method of Hozo et al. [14] to approximate the mean as either: the sample median (if $n > 23$) or mean $\approx$ (min + max + 2*median)/4 if $n \leq 23$. If range and n were reported but no measure of central tendency (i.e., neither median nor mean) was reported, we used a Monte Carlo simulation (100 iterations per study) to estimate the central tendency by sampling n times from a lognormal distribution and constraining the sample minimum and maximum to be the same as those reported in the study. For each iteration, this was done by randomly sampling n times from a uniform normal distribution bounded by $\log_{10}$ transformations of the reported minimum and maximum values (for studies reporting a minimum concentration of 0 or nondetect, we used the continuity correction described above). These n sampled values were then exponentiated, and the mean and median of the set of n exponentiated values were then calculated for this iteration. One hundred iterations were performed, and the resulting 100 replicate estimated parameters (mean and median) obtained were then averaged, with the resulting average used for analysis. If no standard deviation or other measure of variance was reported, we adapted the method of Hozo et al. to estimate this parameter for roughly lognormally distributed data as range/4 for studies with $n \leq 64$ and range/6 for studies with $n > 64$.

Geographic coordinates for each sampling site were obtained from the original study if reported. If a range of coordinates for the study was reported but no specific locations specified, the central (average) value was used. If location was specified in the study by referencing an administrative unit (district, community or settlement, etc.), the centroid of the corresponding administrative unit was approximated using Google Maps and/or maps or descriptors provided by the authors. All coordinates were converted to decimal degree format. For studies reporting multiple observations across multiple locations without specifying the numbers of observations corresponding to each location, the average number of observations was allocated to each location.

Data Analysis

Summary statistics were calculated for aggregated and disaggregated data, including central tendencies of manganese concentrations and proportions of reported concentrations exceeding applicable national standards and international guideline values. Results were also mapped to illustrate geographic trends in data availability and manganese occurrence.

Empirical Bayesian kriging with a power semi-variogram model was performed on collected data to interpolate concentrations in areas where no data were available. Then, using the Esri India 2024 population projection at district levels (Esri, Redlands, CA), a bivariate analysis was conducted to show the intersection of population and estimated contaminant concentrations.

These data were cleaned using R statistical software (R, version 4.4.1) and mapped with ArcGIS Pro (Esri, version 3.1.2). The district level population data were mapped overlayed with the kriged concentrations using a bivariate key, as shown in Figure 10. In some cases, selected values were omitted where there was a mismatch between census districts and map districts – a total of 10 out of 738 districts were omitted for this reason. The geometric intervals were calculated mathematically, giving equivalent or approximately equivalent width and frequency to the three levels for both population and concentration.

Based on the estimates obtained using the above kriging approach, and controlling for the estimated proportion of India’s population relying on groundwater vs surface water, proportions and numbers of populations consuming drinking water exceeding national standards and international guidelines for manganese were calculated, and 95% confidence intervals were estimated. No subgroup analyses or sensitivity analyses were conducted and no other specific methods (apart from estimating confidence intervals) were used to assess certainty.

Risk of Bias

Study quality was assessed for each study using a methodological quality score based on the reporting and adequacy of sample collection, preservation, processing, analysis, and reporting (Table S2). One point was awarded for each quality item that was reported and adequate. Studies scoring above 67% of the maximum possible score were classified as “high-quality.” Risk of bias was assessed by one team member, based on data extracted by one team member. A second team member resolved any questions. Risk of bias among environmental studies was assessed as well. Standard meta-analysis methods such as funnel plots are not directly applicable because they presume that in the absence of bias, study estimates should cluster symmetrically around a single population value, whereas environmental phenomena such as manganese occurrence vary widely across contexts and settings and do not exhibit such clustering over a scale such as a large country. We therefore adapted the underlying principles that 1) sample size and (normalized) measures of variance should not generally predict outcomes of interest in an unbiased set of studies, and that 2) examining the distributions of outcomes of interest for unexplained asymmetries/discontinuities can be useful for detecting biases. In this case, we evaluated the association of mean Manganese concentrations (and log-transformations of the same) with standard deviation, range (max – min), and average number of observations (where reported) among all sample sets and studies, and investigated the distributions of values among all sample sets and studies for unexplained discontinuities as a proxy for bias. We also constructed a lognormal diagnostic plot for the mean manganese concentrations of all sample sets and studies and examined it for unexplained discontinuities and asymmetries. This adaptation was based on prior reports that concentrations of metals in environmental samples are often roughly lognormally distributed [15]. These calculations for risk of bias among studies were conducted by a single team member.

Results

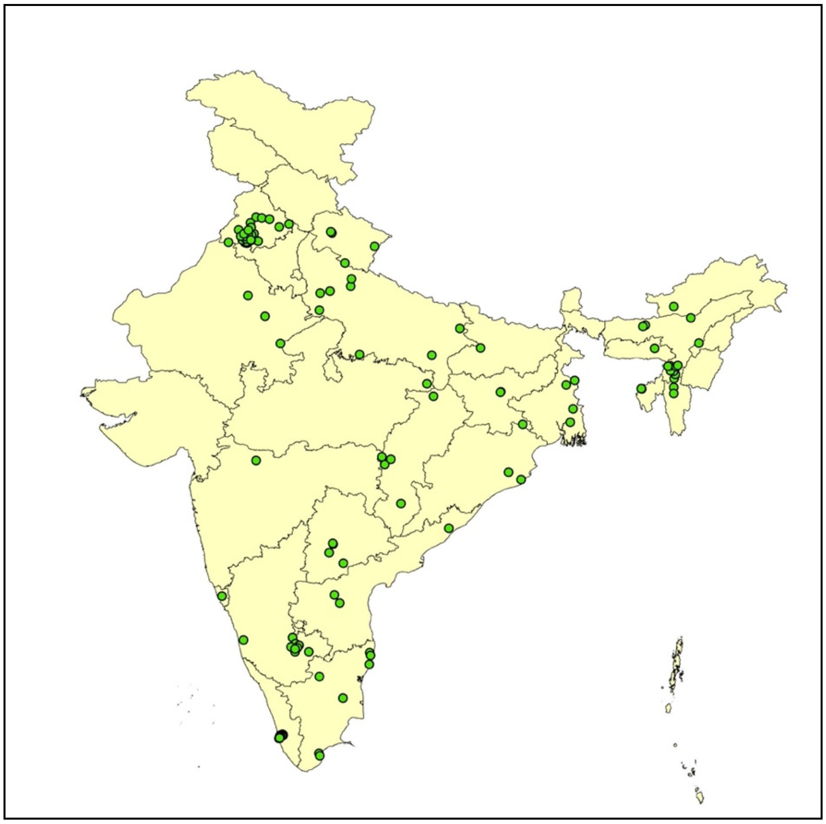


Figure 1: A map of all sampling locations specified in each study. There were 124 unique sampling locations.

A total of 6,397 samples from 124 sampling sites were identified from the 74 included studies (Figure 1, Figure S1). These sites spanned 24 states and 59 districts (Table 2).

For the 59 districts with reported manganese concentration data, log-transformed mean Mn concentrations by district are presented in Figure 2. The district of Dimapur in the state of Nagaland appears to be an outlier with particularly high concentrations of Mn in drinking water samples reported from locations in the district.

Table 2: Number of samples included in each state. There were 168 samples recorded from unspecified states.

State	**No. of Samples**
Andhra Pradesh	50
Assam	1000
Bihar	366
Chandigarh	80
Chhattisgarh	263
Goa	90
Jharkhand	495
Karnataka	270
Kerala	48
Madhya Pradesh	81
Maharashtra	20
Meghalaya	40
Mizoram	14
Nagaland	32
Odisha	225
Punjab	687
Rajasthan	289
Tamil Nadu	417
Telangana	445
Tripura	458
Uttar Pradesh	362
Uttarakhand	203
West Bengal	294
(blank)	168
Total	**6397**

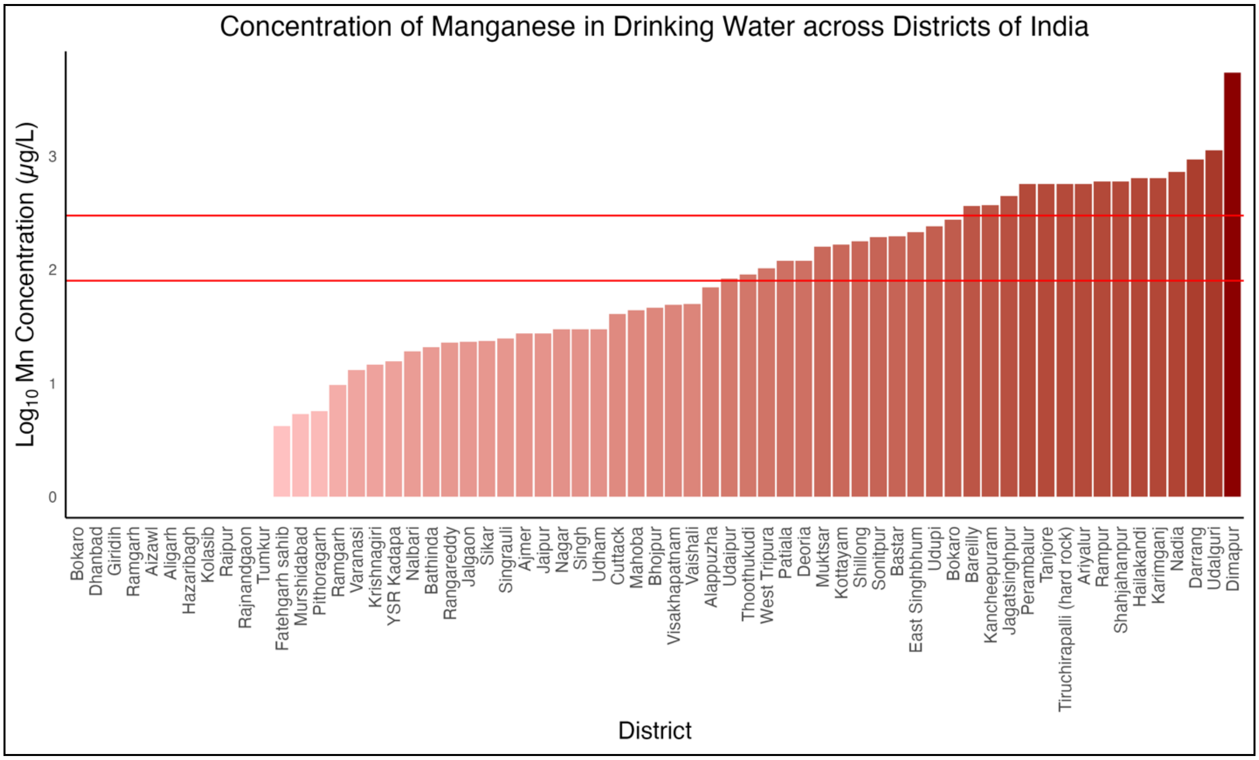


Figure 2: Log$_{10}$ of average manganese concentrations across districts of India.

The distributions of Mn concentrations and log-transformed concentrations are presented in Figures 3a and 3b, respectively. Manganese concentrations in drinking water samples appear to be roughly log-normally distributed. A Kolmogorov-Smirnov test was conducted on Mn concentrations ($p < 0.01$), suggesting that the distribution of concentrations does differ from a log-normal distribution (Figure 4, Table 3).

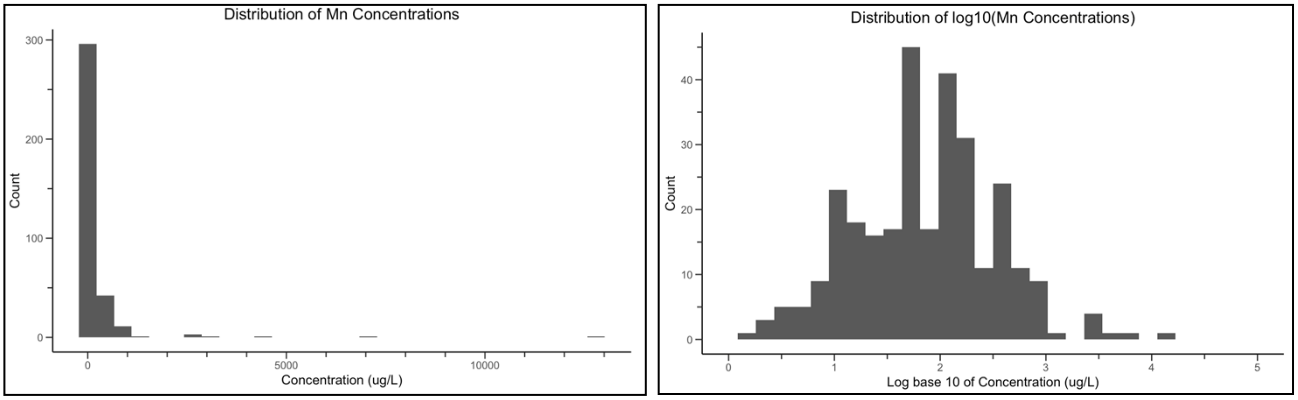


Figure 3a: The distribution of manganese concentrations (left).
Figure 3b: The distribution of the logarithm of manganese concentrations (right).

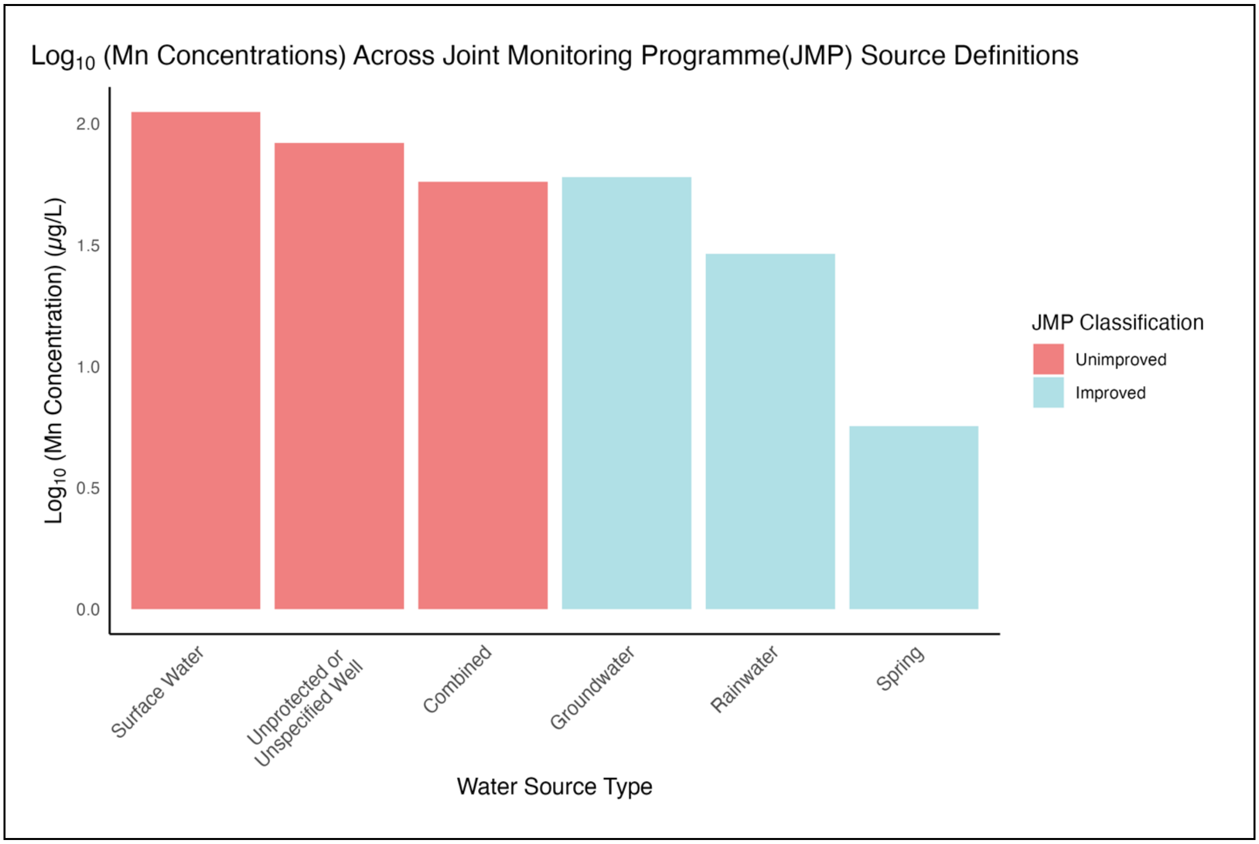


Figure 4: Log-transformed average manganese concentrations by water source type. "Combined" source denotes studies with aggregated samples from more than one JMP source category reported together.

Table 3: Manganese concentrations across water source types. All measurements are in µg/L. "Combined" source denotes studies with aggregated samples from more than one JMP source category reported together.

Classification	**Source type**	**N**	**Minimum**	**Average**	**Geometric Mean**	**Maximum**	**SD**
Unimproved	Surface water	73	0	475.88	121.45	12797.00	1777.98
	Unprotected/ unspecified well	109	0	170.40	82.45	3079.50	412.18
	Combined source	9	9.81	46.91	33.09	120.00	39.23
		191	**0**	**298.56**	**90.72**	**12797.00**	**1149.11**
Improved	Borehole	162	0	154.47	49.44	2733.69	307.02
	Spring	3	0.63	4.00	2.73	5.75	2.92
	Rainwater	1	30	30.00	30.00	30.00	-
		166	**0**	**154.90**	**46.56**	**2733.69**	**305.41**

Figure 5: Manganese concentration distributions for improved and unimproved sources.

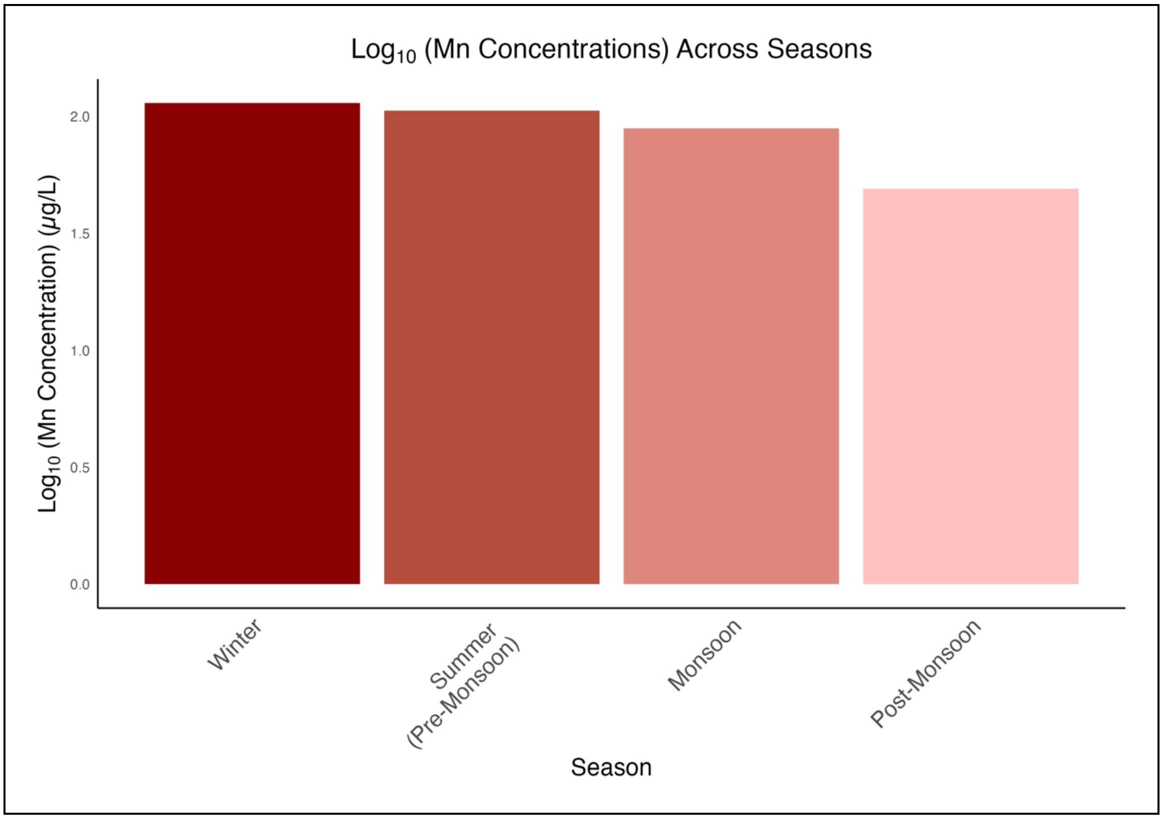


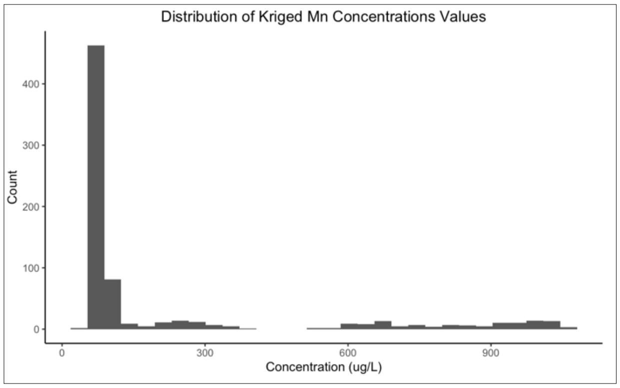
Figure 6: Log_{10} mean manganese concentrations by season (for those studies reporting season).

Table 4: Manganese concentrations across seasons. All measurements are in µg/L.

Season	N	Minimum	Geometric Mean	Maximum	SD
Winter	959	0	0	2733.69	432.28
Summer	497	0	0	2830	376.67
Monsoon	1058	0.8	81.60	400	76.98
Post-monsoon	457	0	0	200	56.09
Not specified	3426	0	0	12797	1231.41

Log-transformed concentrations varied significantly by season (Figure 6, Table 4), as compared using the Kruskal-Wallis test ($\chi^2 = 11.75$, $p = 0.02$). Similar results were found for log-transformed concentrations between improved and unimproved sources ($\chi^2 = 10.61$, $p = 0.001$), as well as source types ($\chi^2 = 24.23$, $p < 0.001$). For each of the three categorizations, untransformed concentrations were not significantly different at an alpha level of 0.05.

Using empirical Bayesian kriging, manganese concentrations were interpolated in districts without any sampling data (Figures 7-8) and categorized using geometric intervals.



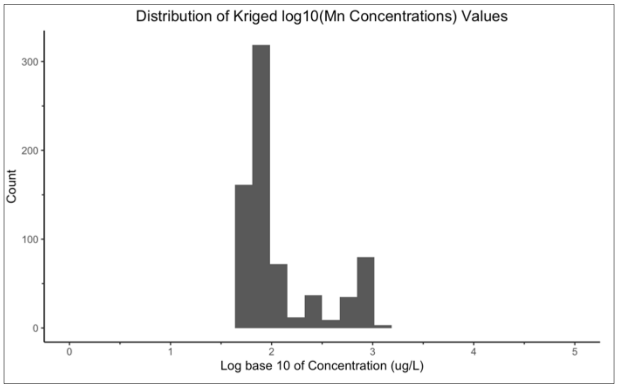


Figure 7a: Distribution of kriged manganese concentrations (left).
Figure 7b: Distribution of the base-10 log-transformed kriged manganese concentrations (right).

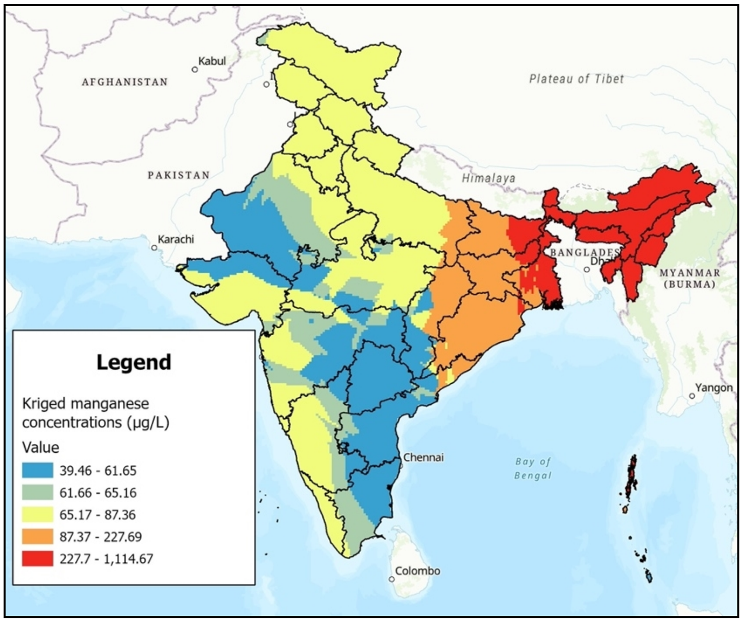


Figure 8: Mean manganese concentrations interpolated at district level using empirical Bayesian kriging.

As of the most recent census of India, conducted in 2011, the population was 1.21 billion; the projected 2024 population is 1.43 billion.[16]

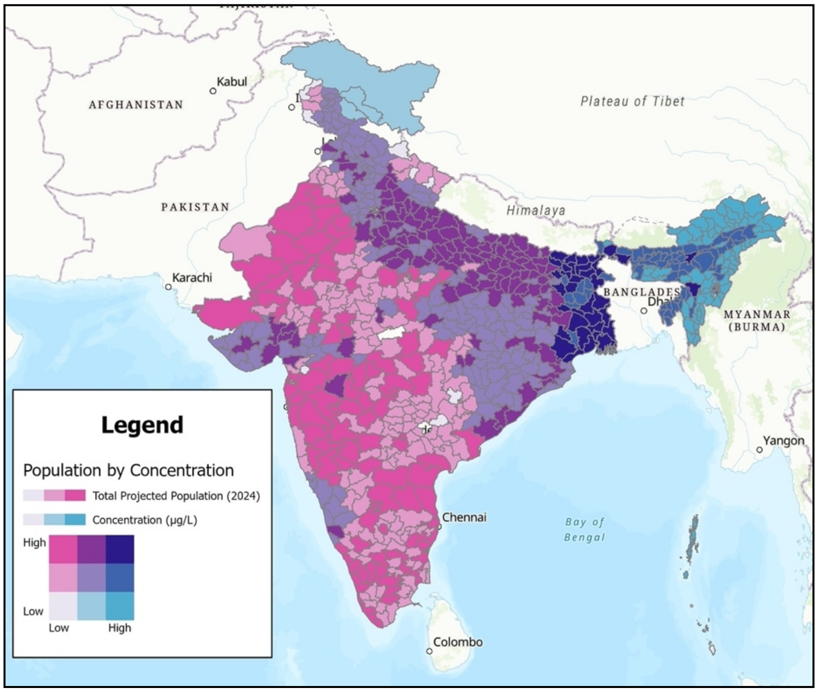


Figure 9: Population-weighted distribution of kriged district-level Mn concentration estimates.

Among disaggregated observations, 7% of samples exceeded the 2011 WHO guideline value (400 µg/L) for manganese in drinking water, 9% exceeded the Bureau of Indian Standards (BIS) drinking water standard (300 µg/L), and 32% exceeded the 2022 WHO provisional health-based GV (80 µg/L). For aggregated data, exceedance proportions were 21% (95% CI: 9-34%), 27% (14-40%), and 58% (40-76%), respectively (Table 5).

According to UNICEF, 85% of rural residents and 48% of urban residents in India rely on groundwater as a drinking water source[7]; the World Bank estimates that in 2022, 36% of residents lived in an urban setting [10]. Based on these values, we can estimate that approximately 72% of India's population relies on groundwater (Table 6). If so, we can infer that approximately 40 million (95% CI: 31-48m) residents (2.7% of total [2.2-3.4%]) may be consuming drinking water with a manganese concentration exceeding the 2011 WHO GV, 59 million (45-73m) residents (4.1% of total [3.1-5.1%]) may be consuming drinking water exceeding the BIS standard, and as many as 323 million (282-365m) residents (23% of total [20-25%]) may be consuming drinking water exceeding the 2022 WHO provisional GV.

Table 5: Percentage of observations that exceed relevant standards and guideline values.

	Disaggregated Observations	**Aggregated Observations (95% CI)**
WHO 2011 guideline value (400 mg/L)	7%	21% (9-34%)
Indian (BIS) Standard (300 mg/L)	9.6%	27% (14-40%)
WHO 2022 provisional GV (80 mg/L)	32%	58% (40-76%)

Table 6: Estimated population relying on groundwater in districts with mean estimated manganese concentrations exceeding relevant standards and guideline values.

	Estimated population reliant on groundwater in areas exceeding threshold (95% CI)	**Percent of national population (95% CI)**
WHO 2011 guideline value (400 mg/L)	39.6 m (30.9-48.3 m)	2.7% (2.2-3.4%)
Indian (BIS) Standard (300 mg/L)	59.0 m (44.9-73.1 m)	4.1% (3.1-5.1%)
WHO 2022 provisional GV (80 mg/L)	323 m (282-365 m)	22.6% (19.7-25.5%)

The quality scores of included studies ranged from 0 to 11, with mean and median quality scores of 5 (Figure 10). Summary statistics are shown in Table 7. Approximately 15% of studies were considered high quality (having a quality score above 8).

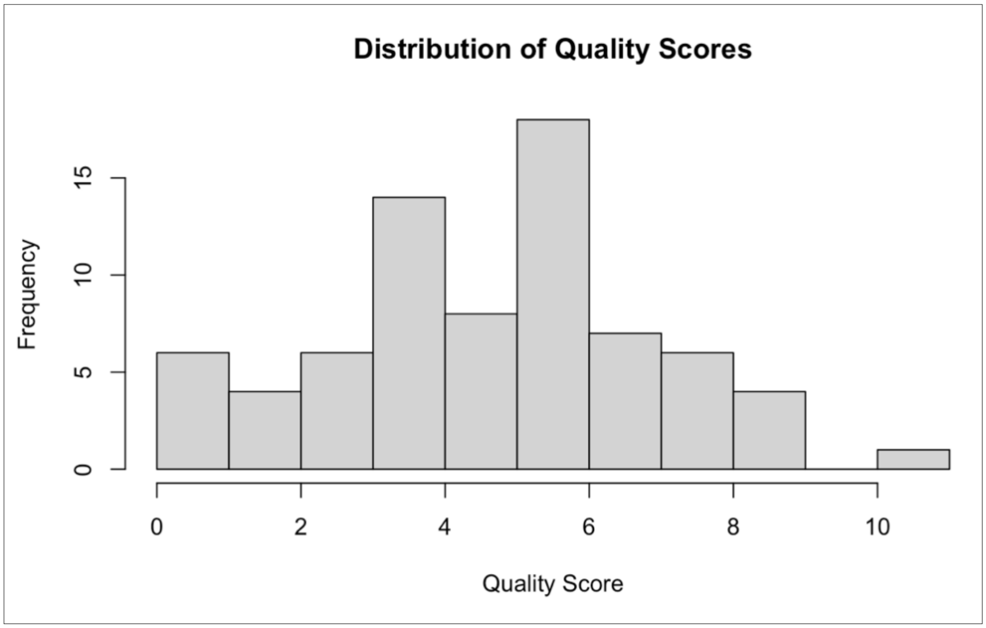


Figure 10: Distribution of quality scores for studies.

Table 7: Summary statistics for the quality assessment of studies.

Minimum	0
1st Quartile	4
Median	5
Mean (SD)	5.1 (2.3)
3rd Quartile	6
Maximum	11

Linear regressions comparing mean manganese concentrations of sample sets in included studies (and log10-transformed mean concentrations) to normalized standard deviation and to average numbers of observations in each sample set showed no significant associations (Table 8). Visual inspection of a lognormal diagnostic plot of manganese concentrations revealed no major unexplained discontinuities over the range of 10-1,000 µg/L and revealed minor departures from lognormality below 5 and above 1000 µg/L (Figure 11).

Table 8: Summary statistics for regressions of central tendency vs measures of variance across all included studies

Measure of central tendency	Measure of variance (or proxy)	n	Prob > F	Risk of bias
Sample Mean [Mn]	Standard Deviation/Sample Mean	86	0.7270	Low
Sample Mean [Mn]	Number of observations	343	0.8554	Low
Log Sample Mean [Mn]	Standard Deviation/Sample Mean	86	0.1201	Low
Log Sample Mean [Mn]	Number of observations	289	0.3762	Low

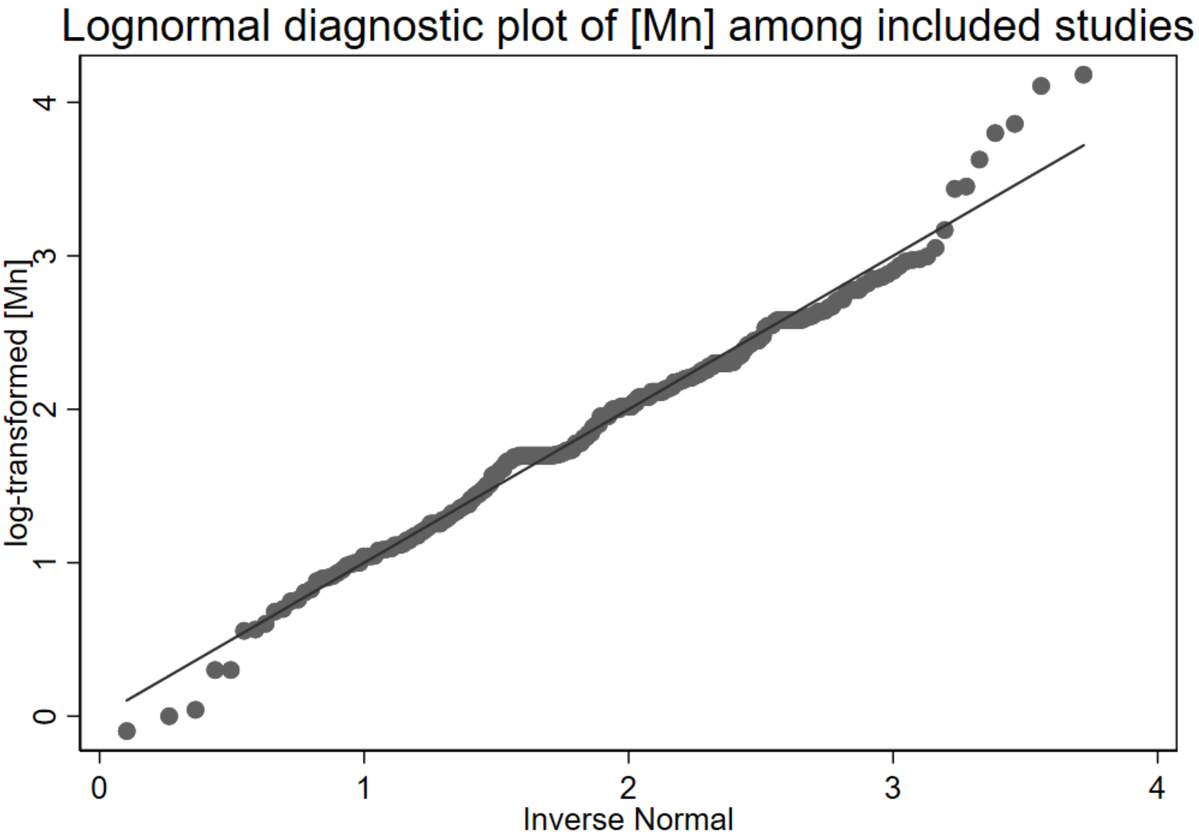


Figure 11: Lognormal Diagnostic Plot of reported mean manganese concentrations in drinking water among sample sets in included studies.

Discussion

These results indicate widespread occurrence of manganese in drinking water in India. Log-transformed manganese concentrations are significantly associated with season and water supply technology type, although un-transformed manganese concentrations are not. Geographic trends are pronounced: high manganese concentrations are found in northeastern India, including Assam and Tripura. The average estimated concentrations decrease to the north and west towards Ladakh and Rajasthan. However, while northeastern India has the greatest overall concentrations of manganese, its population density is not as high as in parts of West Bengal and Uttar Pradesh, where both manganese concentrations and population densities are high, resulting in high "exposure density."

These findings are in line with other studies that have reported widespread occurrence of manganese in drinking water at levels of concern worldwide. Based on the findings from Frisbie and colleagues, several drinking water sources in 54 countries, including Malaysia, Ghana, other LMICs, were found to have manganese concentrations exceeding 400 µg/L, despite the WHO reporting that this value was "well above concentrations normally found in drinking water."[3]

For example, in 1996, the WHO reported that there was a higher prevalence of chronic manganese poisoning symptoms in Greece, where concentrations measured between 1,800 to 2,300 µg/L. Overexposure to manganese leads to a neurological condition called manganism, which has symptoms similar to Parkinson's disease. It is also associated with cardiovascular toxicity and higher infant mortality.[17] With roughly one quarter of the population in the world's most populous country estimated to be drinking water from a source exceeding the 2022 WHO provisional health-based guideline value, the current study adds to growing evidence that manganese contamination in drinking water is an urgent priority for public health.

Within India, prior studies have noted the occurrence of manganese at levels of concern in groundwater sources. Rahman et al. (2023) utilized existing summaries and surveys to identify that increasing population densities by deltaic and river floodplains lead to increased Mn exposure in India.[18] The study reported that 47% of shallow wells sampled in the Bengal Delta exceeded the WHO guideline of 400 mg/L. However, most prior studies are limited to a narrow geographic focus within India, a single drinking water source type, or both. The current work is the first, to our knowledge, that systematically incorporates and expands upon prior studies to provide a national-scale analysis incorporating multiple source types. It also provides a useful comprehensive overview and synthesis of available evidence that could inform potential risk-based approaches to managing exposure to manganese as India works to ensure water safety for all. By synthesizing available evidence on manganese occurrence into a usable and accessible format, this work may be helpful to ongoing efforts to maximize safely managed drinking water services.

The Jal Jeevan Mission (JJM) is a landmark initiative of the Indian government to "provide safe and adequate drinking water through individual household tap connections by 2024 to all households in rural India."[19] These efforts align with international targets under SDG 6, but face challenges including large rural populations (who can be more challenging to reach, especially with piped water services), rapid population growth and internal migration, uneven distribution of surface and groundwater resources, and widespread geogenic groundwater contamination. All of these factors can make achieving universal and equitable access to safe water a lengthier process, and progressive realization of goals and targets may therefore be a de-facto reality in the interim. Synthesizing national-scale evidence on challenges and hazards such as manganese in groundwater, as well as their intersection with population density, may therefore enable policy makers and practitioners organizing monitoring and management to expedite such efforts in settings where these are likely to be the most urgent and impactful in the course of progressive efforts to ensure safely managed and equitable drinking water services for all.

Limitations

The work has several important limitations. The literature included a wide range of study types and qualities, and these studies reported data in many different formats. Integrating aggregated and disaggregated data were challenging, as was classifying data by source type and season where a study spanned more than one such grouping and did not disaggregate results along these lines. Such conflation of potentially very disparate data may tend to underestimate the effects of source type, season, and other such factors.

Similarly, this review did not limit analysis to the highest quality studies, owing to the large number of studies that had one or more limitations; excluding these would have rendered the work impossible. Most studies included in this work had a quality score of 6 or less (Figure 10, Table 7), indicating that while the data exists, it may not capture the true status of the water quality. However, the inclusion of lower quality studies can introduce bias. In the case of studies using less sensitive analytical methods, there is the potential for an upward bias, since noise cannot reduce reported concentrations of trace metals downward below zero, but can increase them infinitely high—thus where noisy measurements of a trace contaminant are included, the tendency is often to bias the overall dataset upwards. However, an examination of the distribution of reported mean values did not indicate large unexplained variance from a lognormal distribution across the range of concentrations most likely to be relevant to environmental manganese exposures of human health concern (10-1000 μg/L), suggesting that the effects of any such bias on the relevance of the current work for decision-making is likely to be modest. Future work should aim to repeat such analyses with only high-quality studies, as increasing numbers of high-quality datasets are published and included. Furthermore, there were fewer studies that reported data for parts of Northern, Central, and Western India, which introduces uncertainty to the analysis. Nationally-representative monitoring of contaminants of concern could provide rich data for this, if feasible.

Another limitation of this work is the need to interpolate observations for studies that report only a limited set of summary statistics. Since studies did not always include all of mean, median, geometric mean, range, etc., a robust method was implemented to ensure that every observation was associated with a concentration value representative of the most likely underlying distribution of values based on the summary statistics reported and reasonable assumptions about the underlying distributions (e.g. roughly log-normal). However, the mean and the range were the most commonly reported summary statistics, and these are not the most reliable options to fit a log-normal distribution of concentrations, so this limitation may have contributed to error and bias in the results. Furthermore, the interpolation of the observations resulted in a distribution that did not resemble the distribution of the raw data (Figure 3, Figure 7), suggesting that the data was transformed significantly.

This work compares manganese occurrence to several different thresholds. This is because evidence and guidance on manganese in drinking water is continuing to evolve. In 2011, the WHO removed its manganese drinking water guideline, because “this health-based value is well above concentrations of manganese normally found in drinking water, it is not considered necessary to derive a formal guideline value.”[3,20] However, roughly 40 million residents in India are consuming water measuring above 400 μg/L. An even greater number are consuming water exceeding the BIS standard of 300 μg/L. This is especially significant since the BIS standard is the enforceable benchmark in India, while WHO guidelines are recommendations without force of law unless incorporated into national standards. As evidence on manganese in water continues to emerge, many countries will debate the question of further adjusting standards to align with new WHO provisional guidance. In the 2023 background document for manganese in drinking water, the WHO derives a provisional health-based guideline of 80 μg/L.[20] Adopting an enforceable standard aligned with this updated provisional guideline could have massive and costly implications for a country with widespread geogenic manganese occurrence, such as India, and the potential health benefits would need to be carefully weighed against costs. This is particularly salient in light of the large uncertainty factor (a factor of 1000) applied in WHO's calculations underpinning its provisional 2022 guideline value. Regardless of the specific methodology and uncertainty margin used, however, it seems likely that progressive reductions in exposure to manganese from drinking water will be beneficial to populations in general, and children in particular. In light of this, we may see many countries progressively reviewing and strengthening regulations around manganese in drinking water in a manner that is both in line with emerging evidence and also informed by dynamic technical and economic constraints. For example, a drinking water standard that may be challenging to achieve when rural piped water coverage is 50% may become more attainable over time as service levels increase.

Implications

Studies like the current work may be helpful to countries seeking to navigate such complexities to chart a path for progressive reduction in exposure to widespread geogenic chemical hazards such as manganese, so that they can both focus current monitoring and management efforts where these may do the most good, and determine where future policy, practice, and research efforts may be most productively targeted. Potential implications for policy, monitoring, practice, and research could include prompting consideration of the following: 1) reviewing national standards for manganese in drinking water; 2) potentially including manganese in nationally-representative water quality monitoring activities; 3) reviewing existing evidence-based solutions for water systems containing manganese at levels of concern; and 4) investigating novel approaches to maximize performance and cost-effectiveness of manganese remediation. The authors stop short of recommending what a sovereign nation might do in response to the evidence synthesized in this work, and will instead highlight items to consider:

1) It may be useful for countries with widespread geogenic contaminants such as manganese to periodically review and, as appropriate, update associated standards and regulations and/or their enforcement in light of emerging and evolving evidence on health effects, updated guidance from WHO and others, and in light of advances in monitoring and management solutions and their own progress on water safety over time.

2) While studies such as the current review can help synthesize published evidence, they are no substitute for systematic and nationally representative monitoring of drinking water safety. Updating monitoring and surveillance activities and test kits (as well as accompanying information management systems) to systematically measure and track manganese concentrations in drinking water could be an impactful next step to better enable risk-based detection and management of this under-recognized water safety challenge. Cost-effective laboratory and field-based Mn test methods are commercially available, making their rapid

integration into ongoing monitoring potentially quite feasible if authorities agree that such data are needed.

3) Where monitoring identifies hazards and regulations provide authority to address them, technologies for prevention and remediation are often needed to solve them, and each of these can present their own logistical and implementation issues to consider. A review of the most efficient and cost-effective solutions for preventing and remediating manganese occurrence in both large and small/decentralized water systems, as well as the adaptation and implementation approaches that have proven most successful in diverse global settings, may therefore be useful in formulating strategies to address such hazards. Common evidence-based solutions such as source substitution, oxidation and filtration (at centralized water treatment plants), and decentralized oxidation/filtration or sorption solutions for small systems are widely used, and others may be considered as well.

4) Finally, future research efforts should review novel and emerging strategies and technologies to better detect and minimize human exposure to high concentrations of Mn in drinking water sources at scale. Such research should consider nominal performance, robustness and sustainability, cost-effectiveness, acceptability, and feasibility/potential implementation challenges associated with adaptation to different water system types across different settings characterized by high concentrations of Mn. Such efforts can help support the practical and sustainable implementation of fit-for-purpose solutions across diverse settings.

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Supporting Information

Table S1: PRISMA Checklist

Table S2. Full Search Strategy

Table S3: Study Protocol.

Table S4: Indicative minimum detection limits for manganese using common analytical instruments and methods.

Table S5: list of included studies

Figure S1: PRISMA Flowchart

Table S6: Study quality items

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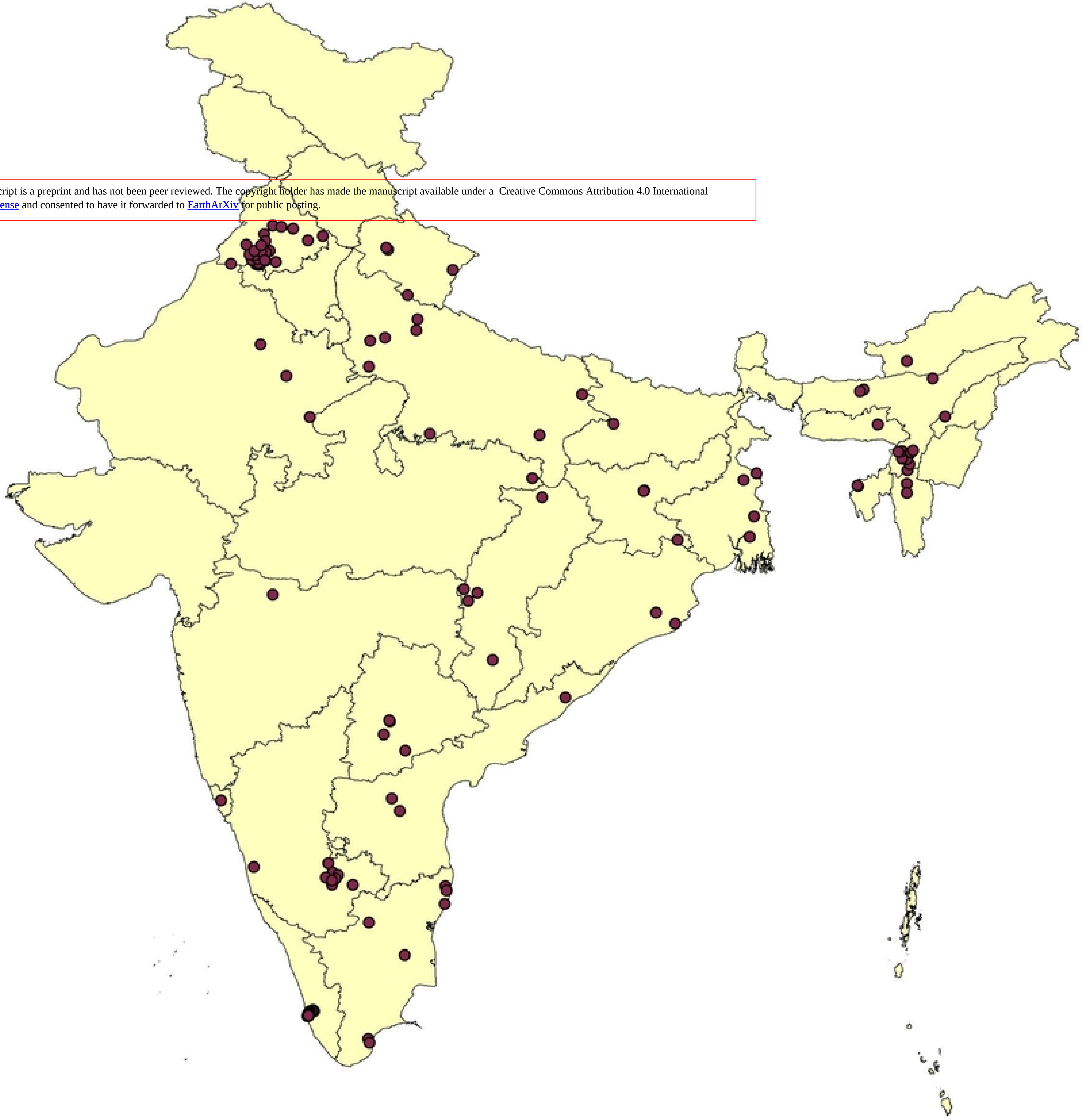
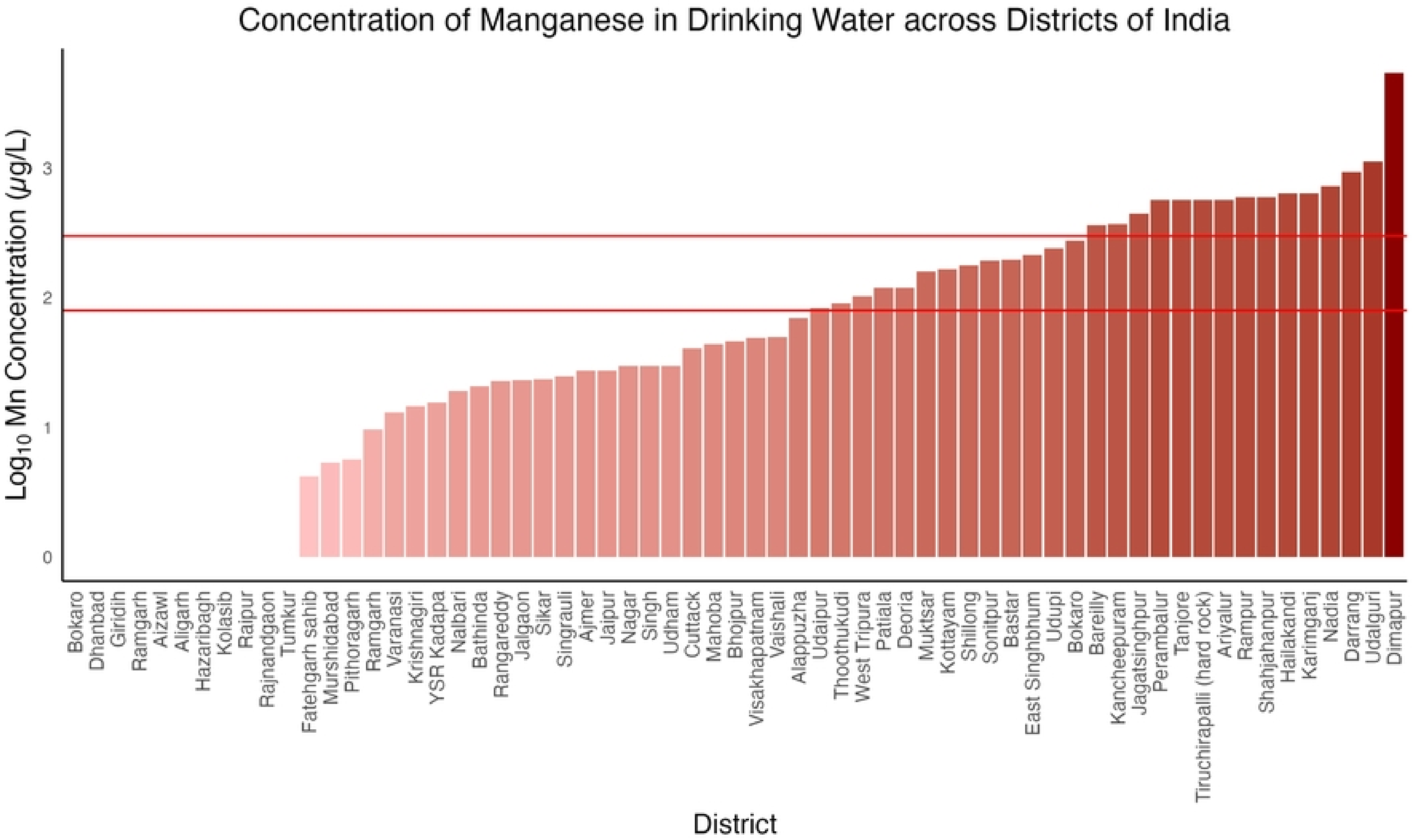


Figure 1



Concentration of Manganese in Drinking Water across Districts of India

Figure 2

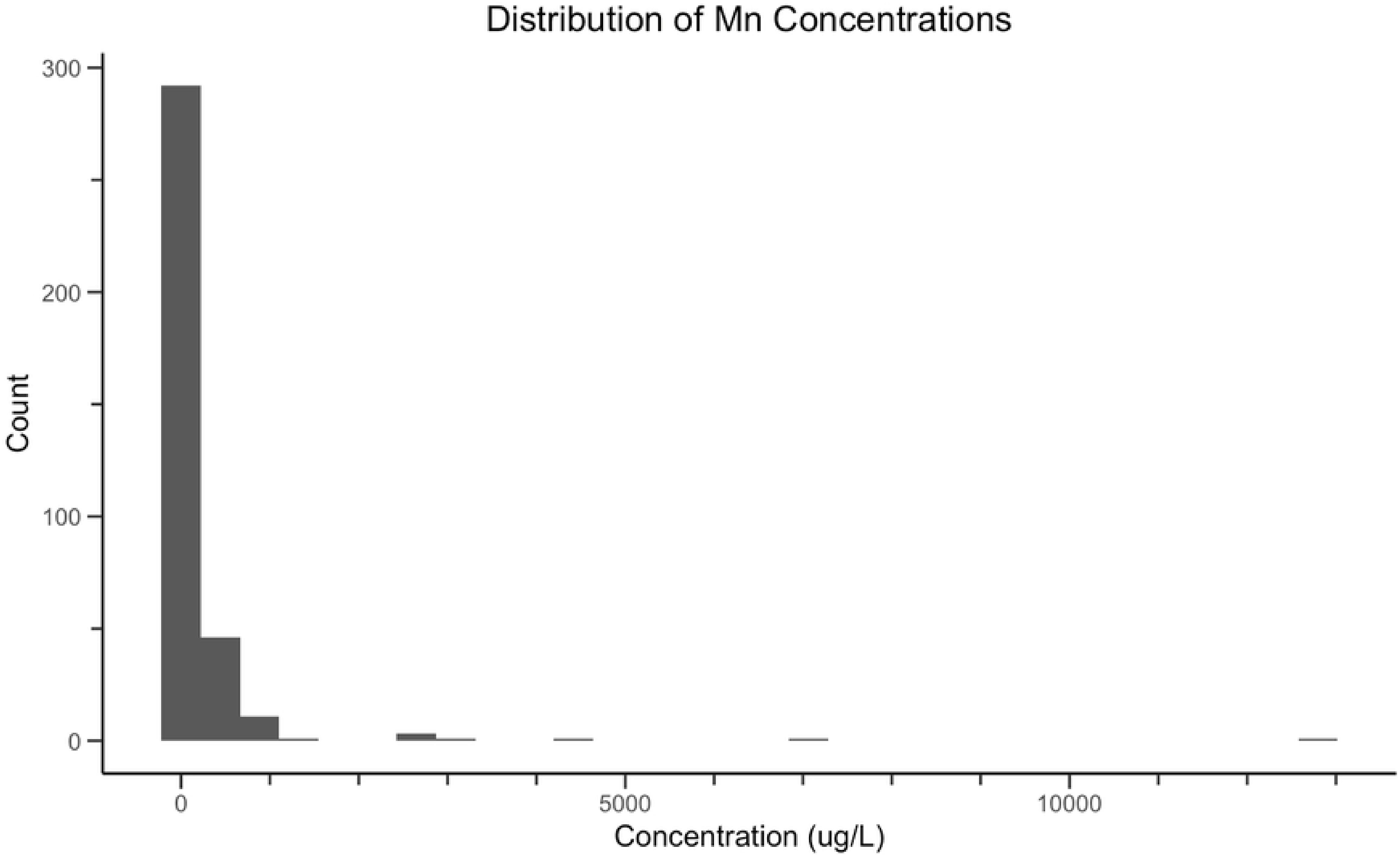

Distribution of Mn Concentrations
Count
300
200
100
0
0
5000
10000
Concentration (ug/L)

Figure 3a

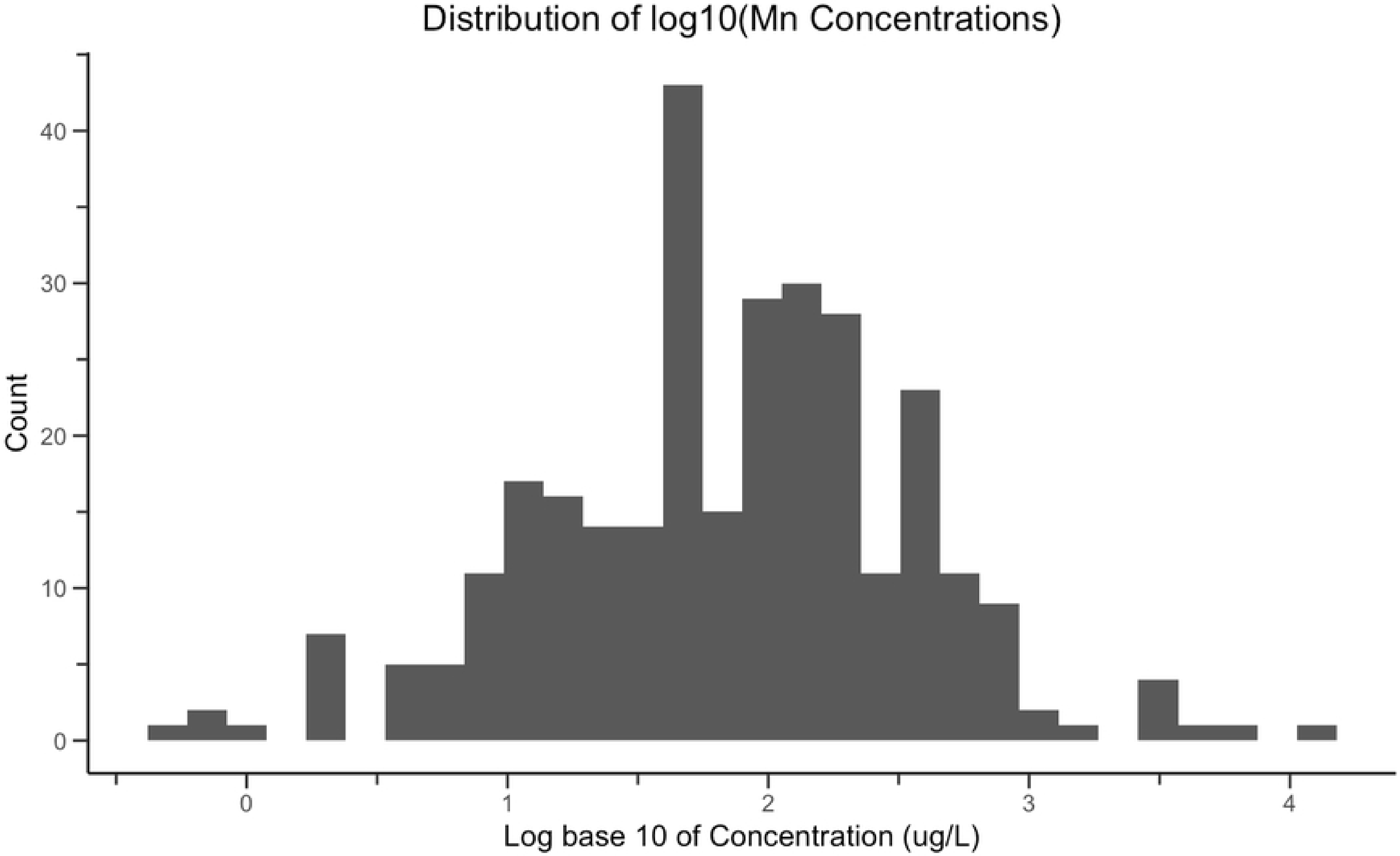

Distribution of log10(Mn Concentrations)
Count
40
30
20
10
0
0
1
2
3
4
Log base 10 of Concentration (ug/L)

Figure 3b

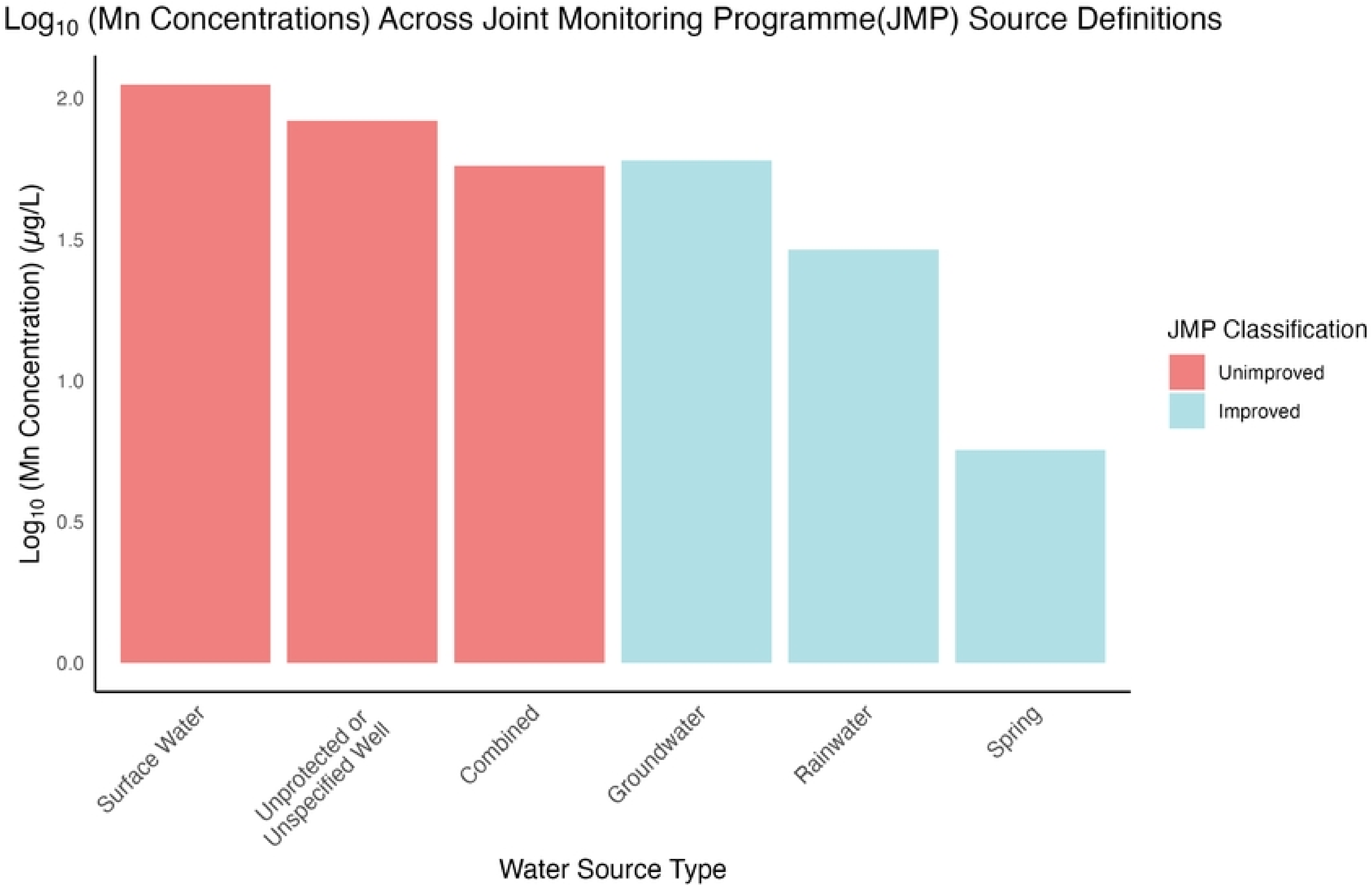

Log$_{10}$ (Mn Concentrations) Across Joint Monitoring Programme(JMP) Source Definitions
Log$_{10}$ (Mn Concentration) (μg/L)
2.0
1.5
1.0
0.5
0.0
Surface Water
Unprotected or Unspecified Well
Combined
Groundwater
Rainwater
Spring
Water Source Type
JMP Classification
Unimproved
Improved

Figure 4


Improved and Unimproved Manganese Concentration
Log$_{10}$ (Mn Concentration) (μg/L)
4
3
2
1
0
0
1
JMP Classification
JMP Classification
0: Unimproved
1: Improved

Figure 5

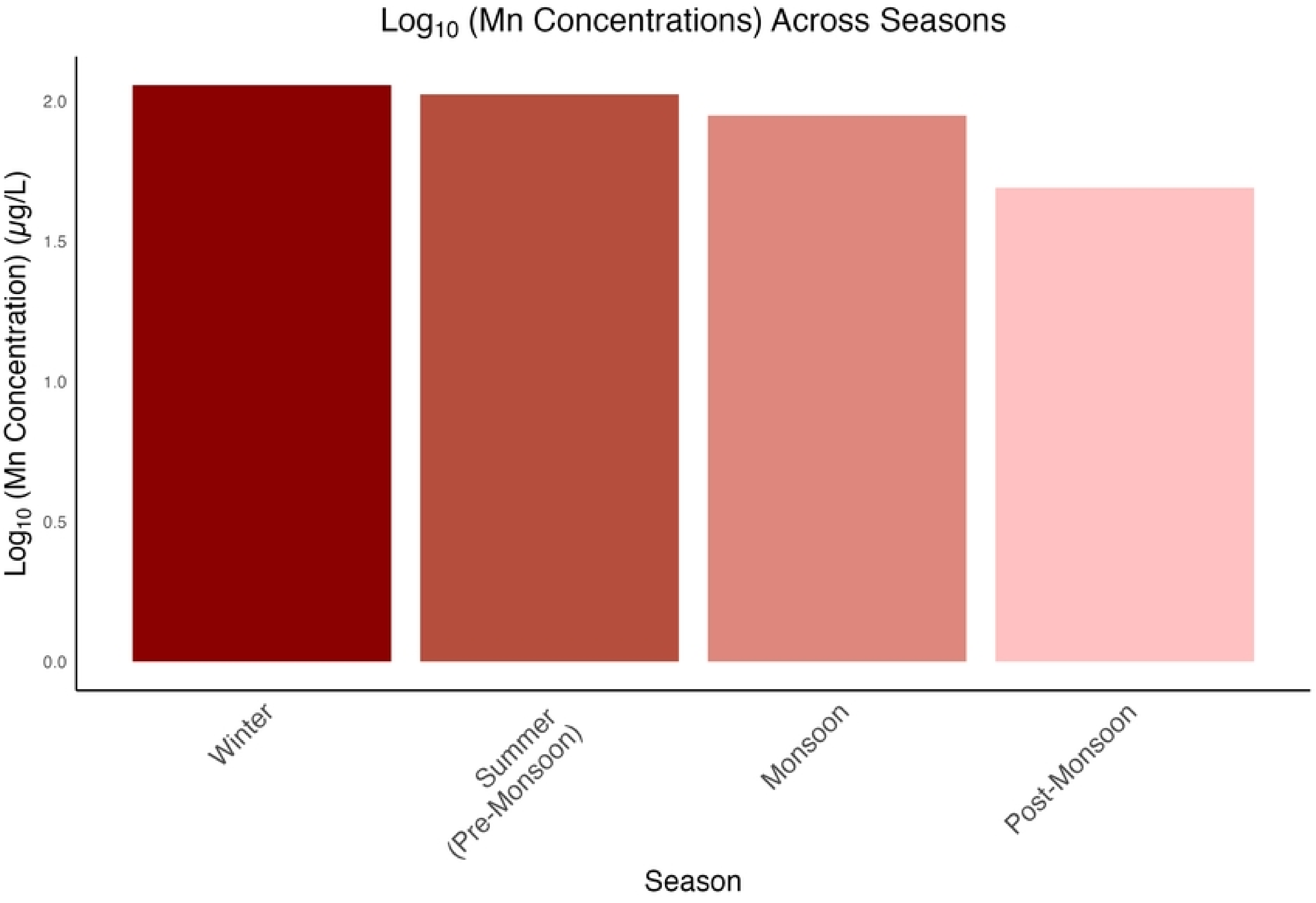

Log10 (Mn Concentrations) Across Seasons
Log10 (Mn Concentration) (μg/L)
2.0
1.5
1.0
0.5
0.0
Winter
Summer (Pre-Monsoon)
Monsoon
Post-Monsoon
Season

Figure 6

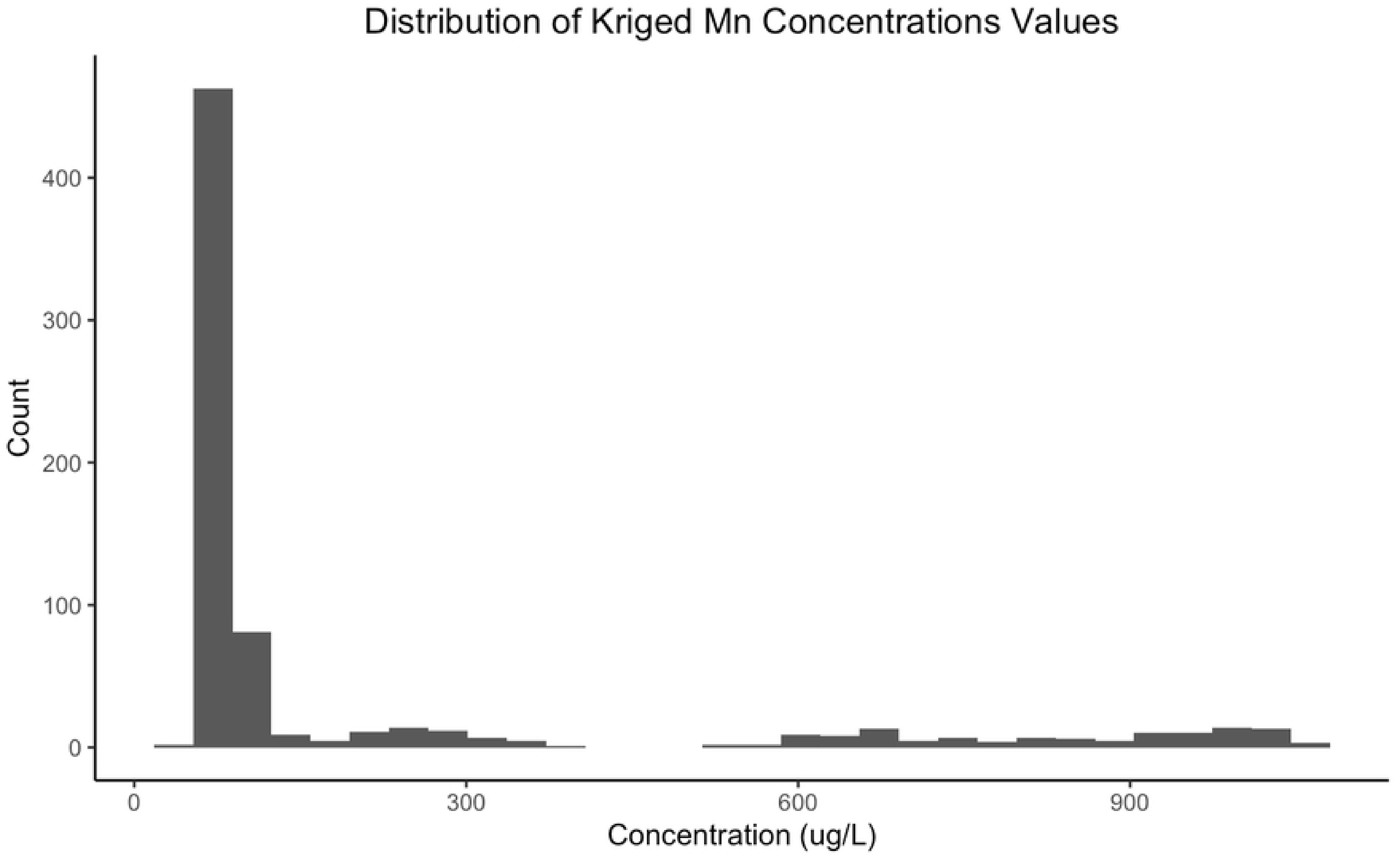

Distribution of Kriged Mn Concentrations Values
Count
400
300
200
100
0
0
300
600
900
Concentration (ug/L)

Figure 7a

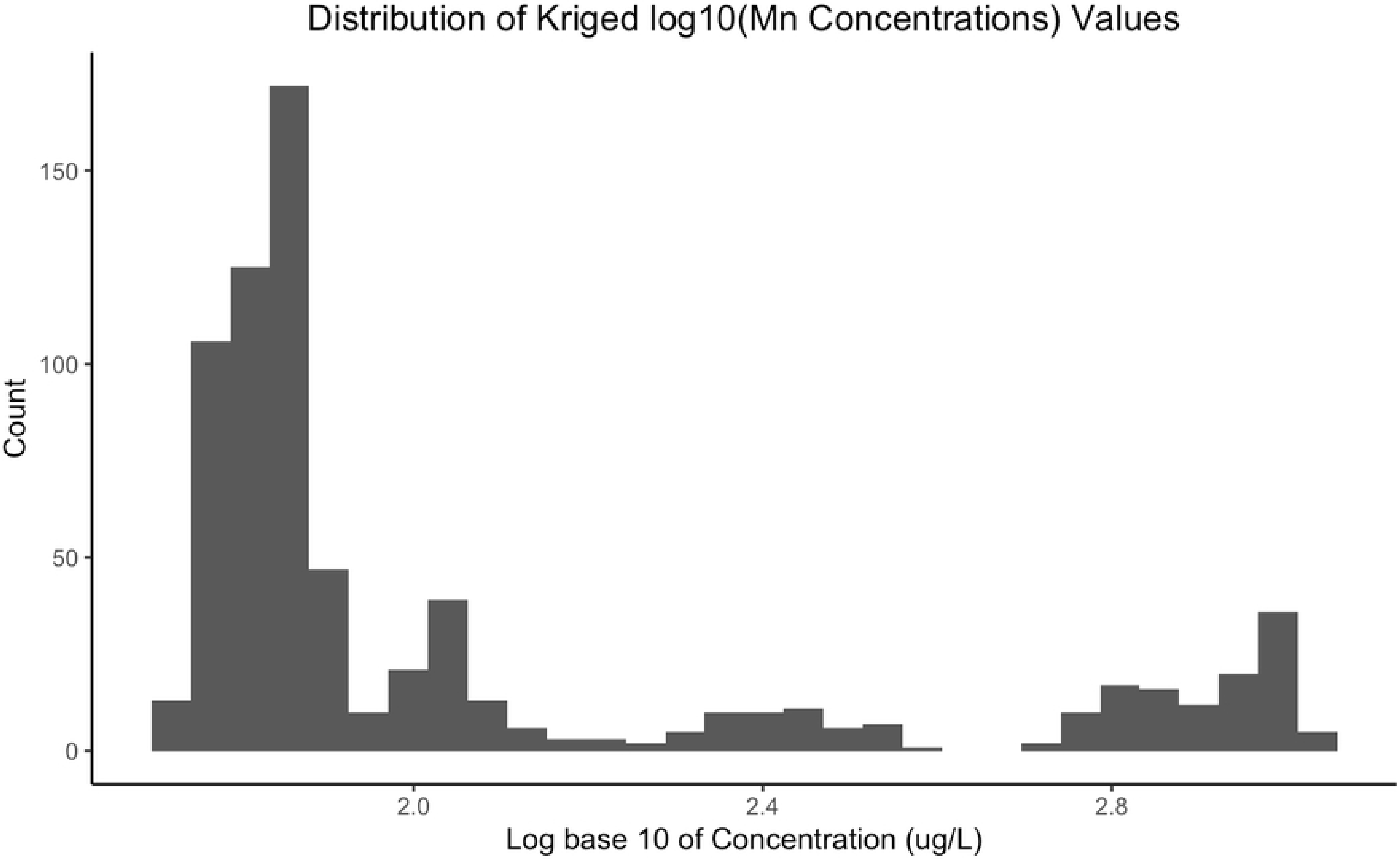

Distribution of Kriged log10(Mn Concentrations) Values
Count
150
100
50
0
2.0
2.4
2.8
Log base 10 of Concentration (ug/L)

Figure 7b

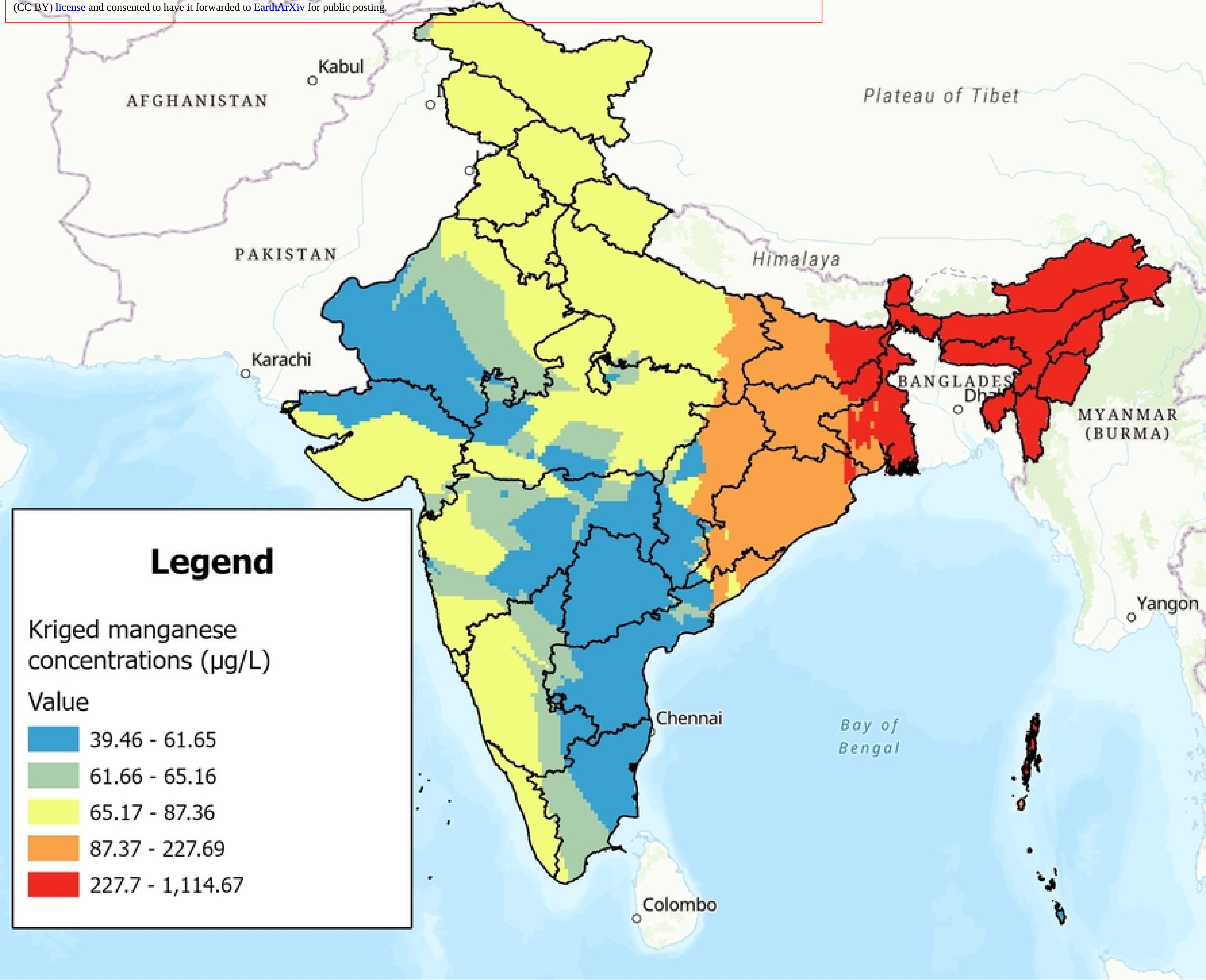

Kabul
AFGHANISTAN
Plateau of Tibet
PAKISTAN
Himalaya
Karachi
BANGLADESH
Dhaka
MYANMAR (BURMA)
Yangon
Chennai
Bay of Bengal
Colombo
Legend
Kriged manganese concentrations (µg/L)
Value
39.46 - 61.65
61.66 - 65.16
65.17 - 87.36
87.37 - 227.69
227.7 - 1,114.67

Figure 8

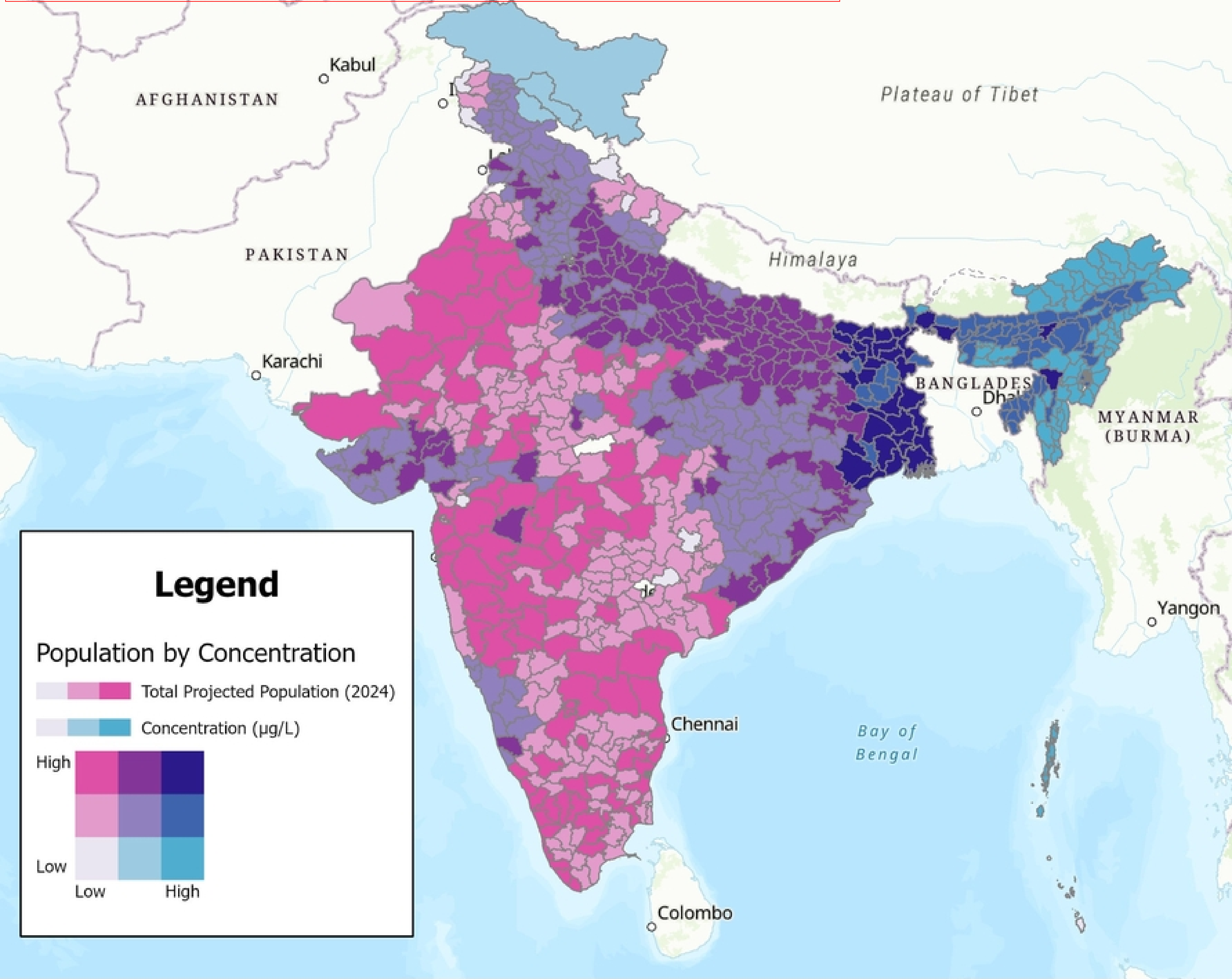

Kabul
AFGHANISTAN
Plateau of Tibet
PAKISTAN
Himalaya
Karachi
BANGLADES
Dha
MYANMAR (BURMA)
Yangon
Chennai
Bay of Bengal
Colombo
Legend
Population by Concentration
Total Projected Population (2024)
Concentration (µg/L)
High
Low
Low
High

Figure 9

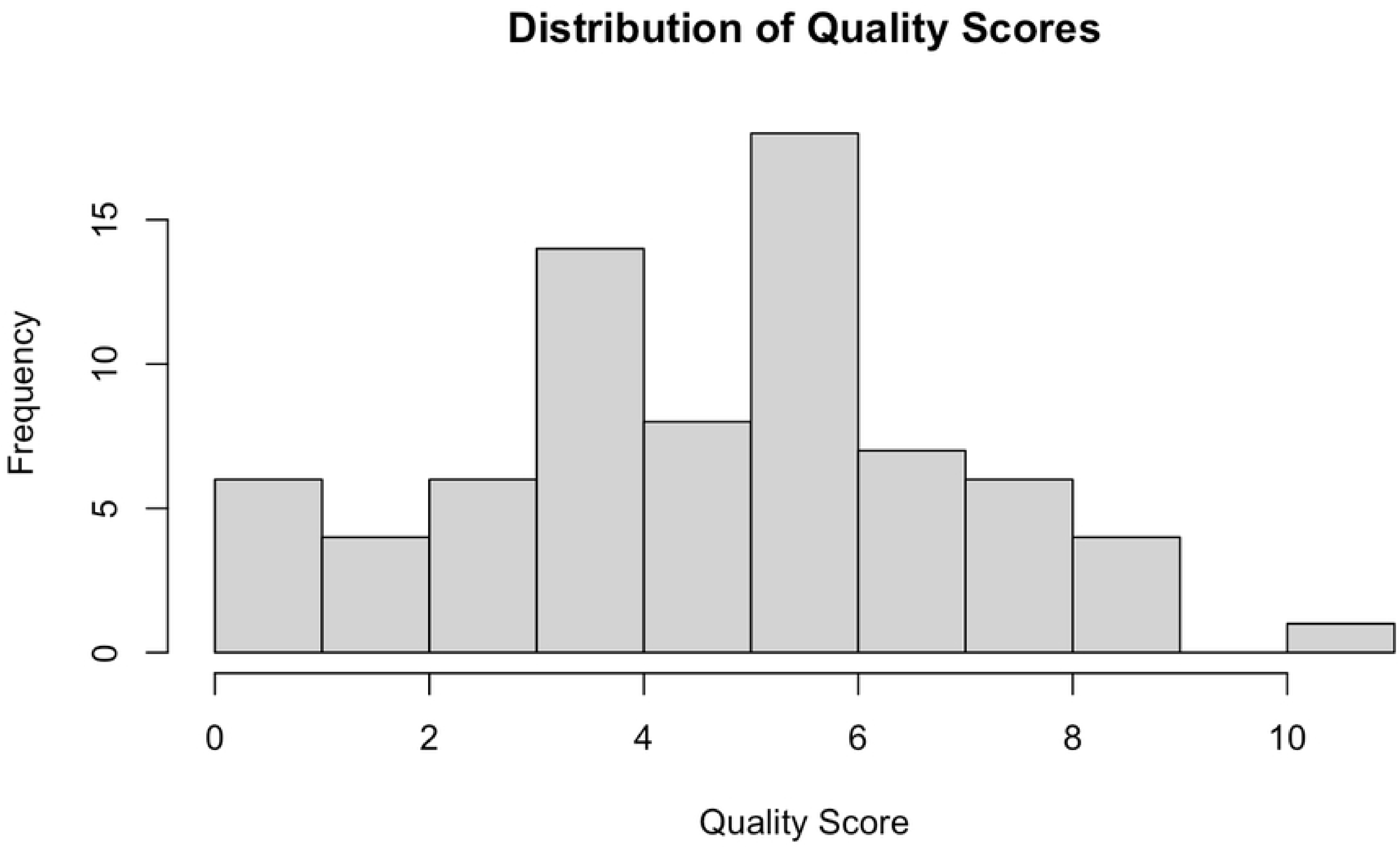

Distribution of Quality Scores
Frequency
0
5
10
15
0
2
4
6
8
10
Quality Score

Figure 10

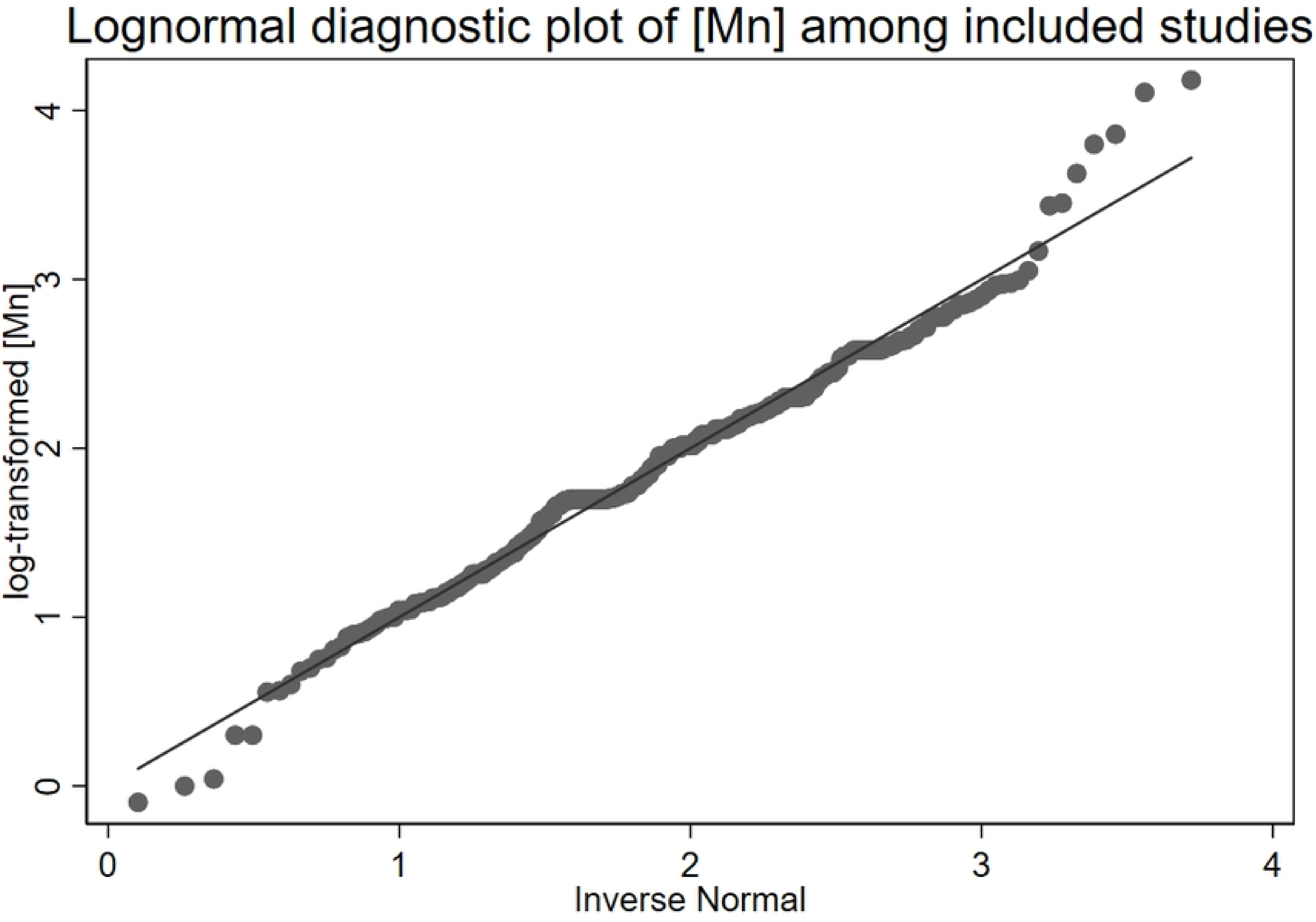

Lognormal diagnostic plot of [Mn] among included studies
log-transformed [Mn]
0
1
2
3
4
Inverse Normal
0
1
2
3
4

Figure 11