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Spatial and socioeconomic inequalities in the access to safe drinking water in Peruvian households

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ABSTRACT

Access to safe drinking water has increased in Peru over the last decades, from 47% (2008) to 52% (2018). Nevertheless, such access would differ according to socioeconomic and regional factors. Thus, this study aimed to assess the socioeconomic inequality in the access to safe drinking water and identify its spatial distribution. We conducted a cross-sectional study based on the secondary data analysis of the 2021 Peruvian Demographic and Health Survey. Access to safe drinking water was a dummy variable categorised as safe if the residual chlorine concentration was $\geq$0.5 mg/L. Nationwide, 29.22% of households had access to safe drinking water. A pro-rich inequality in access to safe drinking water was observed. The spatial distribution was clustered. Significant hotspots were found in the south and centre of the country; however, cold spots were found in most areas. SaTScan analysis identified 32 and 63 significant clusters at high and low risks of having access to safe drinking water, respectively. In conclusion, approximately one out of four Peruvian households has access to safe drinking water, which was mostly concentrated among the wealthier households. Intra- and interdepartmental inequalities in access to safe drinking water were found, with several high-risk clusters.

Key words: drinking water, inequality, Latin America, Peru, spatial analysis

HIGHLIGHTS

- Major socioeconomic and spatial inequalities in the access to safe drinking water were identified.
- The socioeconomic distribution of access to safe drinking water was greatly pro-rich in all departments.
- Nearly half of the richest population and <5% of the poorest population had access to safe water.
- Intra- and interdepartmental inequalities in the access to safe drinking water were found.

INTRODUCTION

The United Nations General Assembly recognised the human right to water and sanitation in 2010 (United Nations 2010). Despite this, access to safe drinking water continues to be a problem worldwide (United Nations 2010; World Health Organization 2022). Nearly two billion individuals consume drinking water contaminated with faeces, constituting a major threat to the health of the population exposed to this substance, causing approximately 80% of infectious and parasitic gastrointestinal diseases and one-third of mortality (829,000 individuals die annually from diarrhoea due to drinking water consumption, sanitation and hand hygiene) (World Health Organization 2022).

Access to water through the public network has increased in Peru in recent decades, and by 2019, 91% of the Peruvian population had this access (Instituto Nacional de Estadística e Informática 2020). Nevertheless, the proportion of people with this access differs according to their region of origin, with higher access in the coastal regions of Peru, which are usually located in areas with greater development, population size and economic growth (Instituto Nacional de Estadística e

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Informática 2020). Furthermore, despite the increase in access to water recently, only approximately 38% of Peruvian households consumed water from the public network with an adequate level of chlorination ($\geq$0.5 mg/L) in 2019 (Instituto Nacional de Estadística e Informática 2020). This proportion is even lower for rural households, in which only 9.2% of cases consumed water from the public network with adequate chlorine levels (Instituto Nacional de Estadística e Informática 2020). In the last decade, access to safe water has increased from 49.1 to 52.4% in medium cities and from 65.6 to 78.4% in large cities; yet, no change in access among small cities has been observed (Hernández-Vasquéz *et al.* 2021). The aforementioned finding suggests the presence of inequalities in access to safe water according to the areas of residence.

In Peru, in 2020, 90.8% (nearly 30 million) of the country's population had access to drinking water from the public water network inside (85.5%) or outside the home (but inside the building or utility pole for public use, 5.3%). According to the place of residence, 5.2% of the urban Peruvian population did not have access to drinking water from the public network. This proportion was higher in the rural population (23.7%). Furthermore, the Peruvian population living in an urban setting has greater access to drinking water inside the home (88.8%) than those in rural areas (73.3%) (Instituto Nacional de Estadística e Informática 2020). Regarding water treatment, areas without access to a water supply network – where water is chlorinated – depend on stored water and employ an Intradomiciliary Drinking Water Treatment System (Ministerio de Salud 2022), which teaches the correct use of alum and chlorine for disinfecting water from unsafe surface sources.

Over the past decade, the use of new analytical techniques to examine public health problems affecting populations has increased. These techniques include the study of inequalities and the use of spatial analysis, which, unlike traditional epidemiological techniques, allows the visualisation, exploration and modelling of spatial disease patterns using geo-referenced data (Jacquez 2000; Pfeiffer *et al.* 2008). The literature describes studies that have employed different spatial analysis techniques for studying health-related problems, including access to safe drinking water (Yang *et al.* 2013; Azage *et al.* 2020; Bogale 2020; Pace *et al.* 2021; Belay & Andualem 2022). In Peru, although few studies have evaluated spatial groupings around drinking water quality (one study has evaluated water quality according to city size) (Hernández-Vasquéz *et al.* 2021), no studies have been identified at the population and regional levels that evaluate socioeconomic differences in access to drinking water, as well as the identification of spatial clustering of drinking water quality in the Peruvian territory. Therefore, the objective of this study was to evaluate the socioeconomic inequality in access to safe drinking water and identify its spatial distribution. Identifying socioeconomic inequalities and spatial clusters of safe drinking water would allow the identification of priority groups for implementing strategies to mitigate the impact of inadequate water quality on the population.

METHODS

Study and design area

The study was carried out in the entire territory of Peru, an upper-middle-income country located in South America that is inhabited by approximately 33 million individuals (Instituto Nacional de Estadistica e Informatica 2022a, 2022b). Administratively, the Peruvian territory is divided into 24 departments and one constitutional province, which together represent the first-level administrative subdivisions. They are further subdivided into 195 provinces and 1,845 districts.

We conducted a cross-sectional study based on the secondary data analysis of the 2021 Peruvian Demographic and Health Survey (ENDES, from the Spanish acronym). The National Institute of Statistics and Informatics (INEI, from the Spanish acronym) annually conducts ENDES. Its survey design was probabilistic, stratified, two-stage and independent, which conferred representativeness at the national, departmental and area of residence (urban or rural) levels. Sampling units consisted of clusters and dwellings in the urban areas and census enumeration areas and dwellings in the rural areas. The household head, their spouse or a person over 18 years old (Peruvian Age of Majority) answered the Household Questionnaire. However, the spatial coordinates were obtained from the location of the sampling clusters. In 2021, 3,254 sampling clusters were included, which contained 36,760 households. Additional details of the 2021 ENDES are described elsewhere (Instituto Nacional de Estadística e Informática 2022a, 2022b).

Inclusion criteria

The ENDES selected the sample in two steps: first, the primary sampling units (conglomerates), based on the 2017 Peru Population and Housing Census, were selected with probability proportional to size sampling, considering occupied dwellings weights. Second, secondary sampling units (dwellings) were selected from the dwellings register by balanced sampling for better estimations. However, we included only households where the interviewers measured water chlorination.

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Safe drinking water

Access to safe drinking water was a dummy variable (yes/no), measured based on water chlorination. It was categorised as 'safe drinking water' according to the Peruvian Water Quality Regulation (Ministerio de Salud 2011) and World Health Organization (WHO) recommendations (World Health Organization 2017), which consists of a residual chlorine concentration $\geq$0.5 mg/L. This concentration warrants effective disinfection. Otherwise, it was categorised as 'unsafe drinking water'. Surface water sources without chlorination (e.g. river, spring and well) were considered as having a chlorine level of 0.0 mg/L. Concerning the measurement procedure, interviewers were provided with a free chlorine color disk test kit (HACH$^{®}$, model CN66-FA) and filled two 5 mL tubes with samples from water sources where chlorination was performed, preferably from the kitchen faucet; or, in the absence of a supply network, from a storage container. Then, a diethyl-p-phenylenediamine tablet was added to one tube and shaken until dissolved. The other tube served as a control. The results were read using the disk. Further details are described in the ENDES interviewer manual (Instituto Nacional de Estadística e Informática 2021).

Socioeconomic status

In the absence of a direct measurement of socioeconomic status (SES), we used the wealth index, which is based on an asset-based approach. The ENDES definition of the wealth index considers multiple aspects such as household characteristics, measure or crowding, property ownership and access to goods and services, among other factors. This variable was classified into five quintiles. For better understanding, we renamed them into poorest, poor, middle, rich and richest. It was calculated using the principal component analysis method (Rutstein & Johnson 2004).

Statistical analysis

The inequality analysis was performed through the *Lorenz* (Jann 2016) and *Conindex* (O'Donnell *et al.* 2016) packages in STATA version 16.0 (Stata Corporation, College Station, TX, USA). We constructed concentration curves (CCs) and calculated the Erreygers' normalised concentration index (ECI). A CC is a graphical representation of the distribution of a health variable against the SES: from the poorest to the richest. In this study, access to safe drinking water was represented in the y-axis, whereas the wealth index was represented in the x-axis. If the curve is below the line of equality (45° line), the variable is distributed among the richest. Otherwise, if it is above the line of equality, it means that it is distributed among the poorest. To quantify the magnitude of inequality, the ECI was calculated. The range of the ECI was from -1 to $+1$. Positive values imply that the variable has a pro-rich distribution, whereas a negative value implies a pro-poor distribution. The ECI corrects the drawback of the traditional concentration index (also known as the Gini Index) for binary variables, as it satisfies some properties such as properties of transfer, level independence, cardinal invariance and mirror (Erreygers 2009).

Regarding the spatial analysis, we plotted the departmental access to safe drinking water on a choropleth map. Likewise, Global Moran's I, hotspot analysis (Getis-Ord-Gi*) and Kriging interpolation were performed in ArcGIS (ESRI, Redlands, CA, United States of America). All spatial data were projected to UTM Zone 18. Global Moran's I is a measure of spatial autocorrelation, and its values range between -1 and $+1$. A positive value implies a clustered distribution, zero implies a random distribution and a negative value implies a dispersed distribution. The hotspot analysis (Getis-Ord-Gi* statistics) statistics provides z-scores and associated p-values for each observation. It maps statistically significant hotspots or coldspots deepening upon positive or negative z values, respectively, over the area of study. The z-values near zero are considered insignificant. Additionally, ordinary Kriging spatial interpolation predicted access to safe drinking water in the unsampled areas based on the sampled areas.

Bernoulli-based Kulldorff spatial scan statistics were performed in SaTScan™, version 10.1, which employs a circular scanning window that moves systematically around the study area for detecting clusters. To fit the Bernoulli model, households with access to safe drinking water were considered cases, whereas those without access to safe drinking water were considered controls. To identify both small and large clusters, we set the maximum size of the clusters at 50% of the population. A log-likelihood ratio (LLR) was calculated for each potential cluster, and it was based on 999 Monte Carlo replications. When the LLR was greater than the Monte Carlo standard critical value, considering a significance level of 0.05, the cluster was considered statistically significant. Moreover, a relative risk (RR) was calculated for each potential cluster, indicating that the risk of having access to safe drinking water is higher inside than outside the cluster window. The high-risk clusters were red-coloured ($\mathrm{RR} > 1$), whereas the low-risk clusters were blue-coloured ($\mathrm{RR} < 1$). Finally, the clusters were ranked based on their RR (Kulldorff 1997).

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Ethical considerations

This study was based on the secondary analysis of the ENDES, which is freely available in the public domain on the 'Microdatos' website of INEI (http://iinei.inei.gob.pe/microdatos/). The units of analysis were anonymised households. Thus, ethical approval was not required.

RESULTS

Characteristics of the households

Data from 31,811 households were included (Supplementary 1). Most homes were in urban settings (78.5%). Likewise, 33.57% of the households were from Lima Metropolitan, 26.19% from the rest of the coast, 26.62% from the highlands and 13.62% from the jungle. Regarding the wealth index, 20.97% of the households were poorest, 20.62% were poor, 20.2% were middle, 19.17% were rich and 19.05% were richest. Most households had a piped water supply (74%) as the main source of water supply. Furthermore, 29.22% (95% CI 28.00–30.47) had access to safe drinking water. The proportion of households with a chlorine concentration of 0.0 mg/L was 44.05%. Moreover, 11.55% of the households took packed water. Regarding the chlorine concentration, according to the wealth index, the major wealth index had a higher concentration of chlorine. Indeed, 49.9% of the richest and 4.7% of the poorest populations had access to safe water (Figure 1).

Inequality analysis

A pro-rich inequality was observed in access to safe drinking water among Peruvian households (ECI = 0.3137). (Figure 2(a)) When stratified by departments, the highest pro-rich inequality was found in Pasco (ECI = 0.4273), followed by Ayacucho (ECI = 0.3337), Huancavelica (ECI = 0.2994) and Arequipa (ECI = 0.2635) (Figure 2(b) and Supplementary 2).

Spatial analysis

The spatial distribution of access to safe drinking water showed significant spatial variations across the country. The access to safe drinking water ranged between 1.24 and 53.90% among departments. The highest access was in Callao (53.90%), followed by Lima (47.33%), Moquegua (47.24%) and Tacna (45.59%). Meanwhile, Ucayali (3.12%), Cajamarca (5.81%) and Pasco (1.24%) had the lowest access (Figure 3(a)). Additionally, the spatial distribution was clustered (Global Moran's $I = 0.62$, p value < 0.0001) (Figure 4). The hotspot analysis (Getis-Ord-Gi* statistic) found significant hotspots in the south and centre of the country. Coldspots were found in most areas of the country (Figure 3(b)). The Kriging interpolation

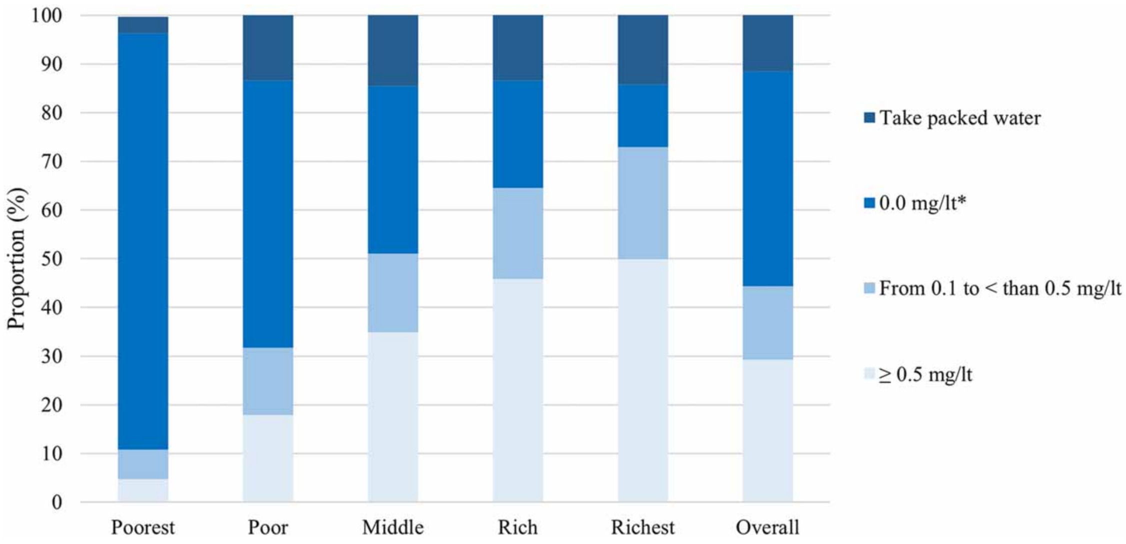

Figure 1 | Chlorine test results of drinking water in Peruvian households by wealth index. *Those households whose water source was the river, spring, well, etc., were considered as having a chlorine concentration of 0.0 mg/lt.

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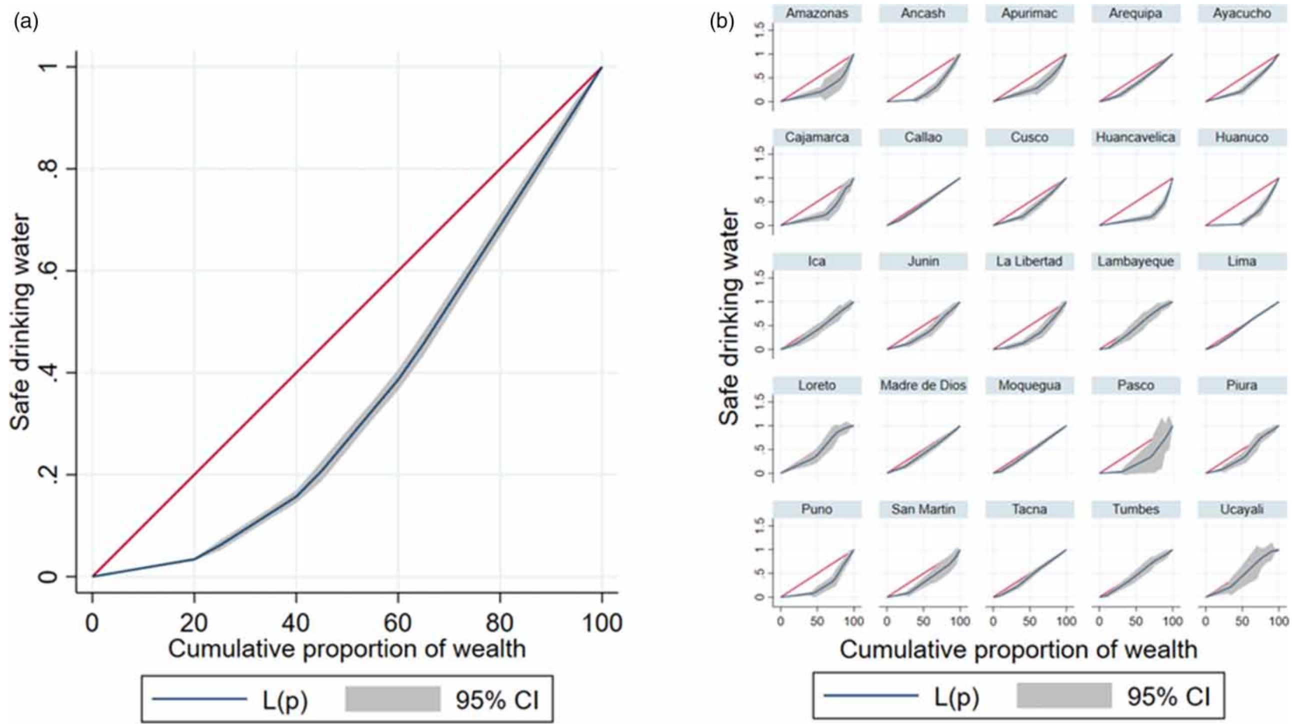

Figure 2 | Concentration curve of safe drinking water in Peruvian households. (a) General index of access to safe drinking water. (b) Stratification of access to safe drinking water by the department.

predicted high access to safe drinking water in some areas of Lima, Moquegua, Tacna and Amazonas. However, most areas under study had low predicted access (Figure 3(c)).

The SaTScan analysis identified 4,124 clusters, of which 95 were statistically significant. Of these, 32 and 63 were at a high and low risk of having access to safe drinking water, respectively (Figure 3(d)).

DISCUSSION

Main findings

Major socioeconomic and spatial inequalities in access to safe drinking water were identified across the Peruvian national territory in 2021. The same situation occurs with some 1.8 billion citizens of the world (Otter *et al.* 2020). The socioeconomic distribution was greatly pro-rich in all departments. Approximately only one out of four Peruvian households had access to safe drinking water; however, most households had a piped water supply. Nearly half of the richest population and <5% of the poorest population had access to safe drinking water. The lowest access to safe drinking water was also found in the natural regions of the Peruvian highlands and jungle. Moreover, a highly clustered spatial distribution pattern was observed, which is expected because most houses have similar water supplies in neighbouring areas. They were in the central and southern regions of the country, but mainly in the highlands. Access to safe drinking water is a cornerstone of public health and a human right. Therefore, ensuring its availability countrywide is of utmost importance.

Plausibility of the results and comparison with previous studies

Although most Peruvian individuals have access to a water supply network (piped water), our findings imply that it does not meet the minimum safety standards related to chlorine concentration. Most studies have focused on improved and unimproved water sources rather than quality evaluation defined by direct measurement of chlorine concentration (Hasan & Alam 2020; Local Burden of Disease WaSH Collaborators 2020). Our results revealed that access to safe drinking water increased with SES and that approximately four out of 10 households relied on non-chlorinated water. This quality gap may be explained by various administrative, financial, technological and community aspects (Ministerio de Desarrollo e Inclusión 2020).

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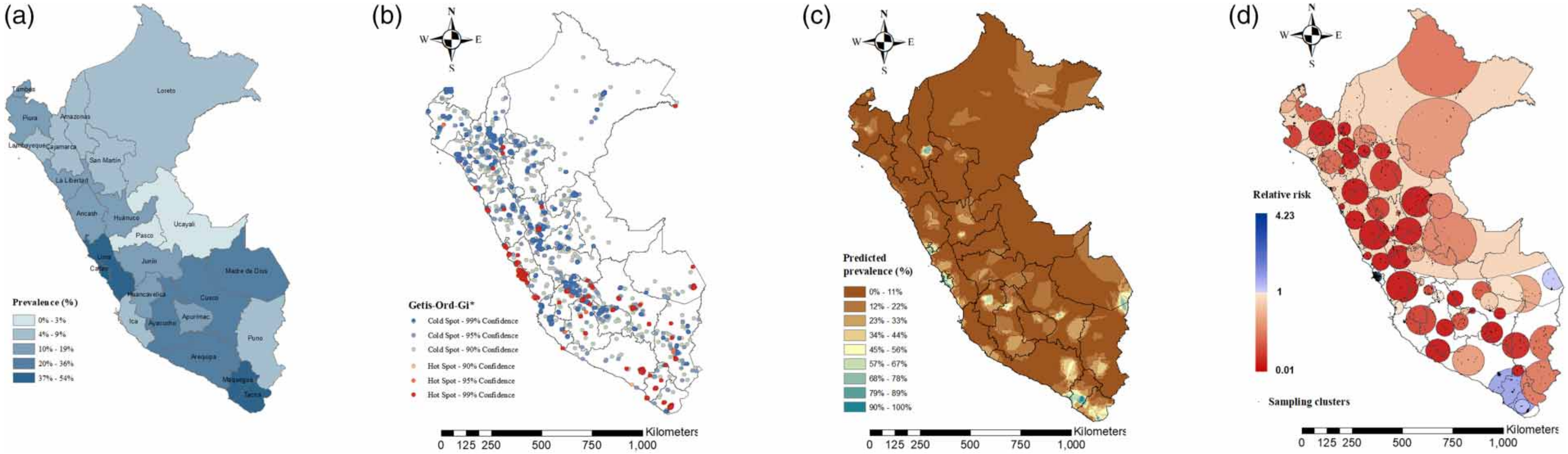

Figure 3 | Spatial analysis of safe drinking water in Peruvian households. (a) Prevalence of safe drinking water in Peruvian households, (b) cold and hot spots of safe drinking water in Peruvian households (Getis-Ord-Gi*), (c) predicted prevalence of safe drinking water in Peruvian households (Kriging interpolation), (d) low- and high-risk clusters of safe drinking water in Peruvian households (Bernoulli-based spatial scan statistics).

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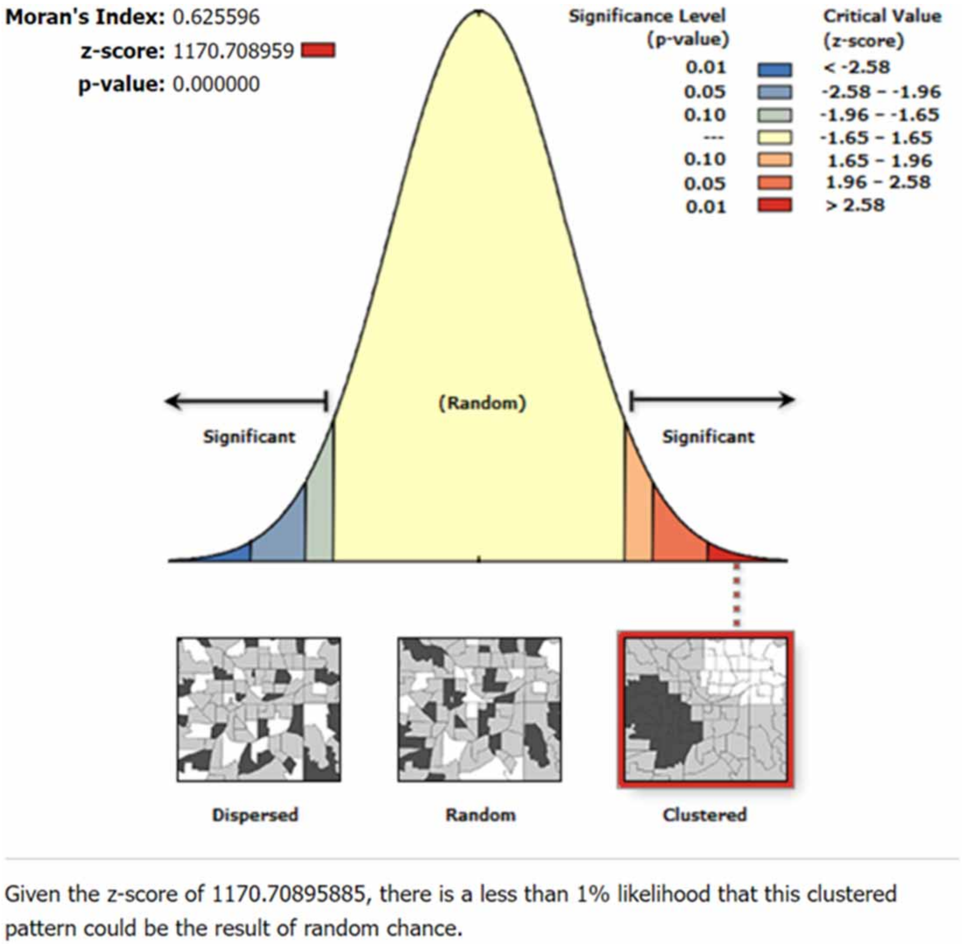

Moran's Index: 0.625596

z-score: 1170.708959 🟥

p-value: 0.000000

Significance Level (p-value)		Critical Value (z-score)
0.01	🟦	< -2.58
0.05	🟦	-2.58 - -1.96
0.10	🟩	-1.96 - -1.65
---	🟨	-1.65 - 1.65
0.10	🟧	1.65 - 1.96
0.05	🟧	1.96 - 2.58
0.01	🟥	> 2.58

Given the z-score of 1170.70895885, there is a less than 1% likelihood that this clustered pattern could be the result of random chance.

Figure 4 | Global Moran's *I* (spatial autocorrelation) of access to safe drinking water.

An unequal socioeconomic distribution in the access to safe drinking water favouring the wealthiest groups was found, as observed in previous studies from Mexico (Morales-Novelo *et al.* 2018), Ethiopia and South Africa (Hasan & Alam 2020; Oskam *et al.* 2021). These results show that SES is crucial for proper drinking water accessibility, as we expected. A socioeconomic inequality analysis of the access to safe drinking water according to city size was performed in Peru. This study also described a greater concentration of access to safe drinking water among the population of a higher wealth quintile (Hernández-Vasquéz *et al.* 2021). However, the geographical distribution was not assessed, and different data were used. Given the need for universal access to safe drinking water and the fact that groups with lower SES have historically presented a greater burden of diseases transmitted through unsafe water, increasing access to safe water through the public network is paramount; furthermore, ensuring that this is accompanied by an optimal quality of drinking water is essential.

The identification of high-risk clusters of low access to safe drinking water agrees with data reported by other governmental information sources. We aimed to provide well-defined areas by performing spatial analysis and assuring greater comparability with the usage of the most recent Peruvian demographic and health survey and a more detailed description of water sources and quality. This study showed inter- and intradepartmental disparities in access to safe drinking water and identified both high- and low-risk clusters and hot and cold spots. These geographical areas of low access to safe drinking water were located in the central and south regions of the country, corresponding to the Andean regions, most of which have the lowest economic development countrywide (Instituto Nacional de Estadística e Informática 2020). According to the literature, many low- and middle-income countries showed similar spatial patterns, although some studies have examined unimproved water sources (Anthonj *et al.* 2020; Azage *et al.* 2020; Bogale 2020; Belay & Andualem 2022). Overall, the improvements and broadening in access to safe drinking water should be accompanied by interventions for waterborne diseases.

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Socioeconomic and geographical inequalities across the Peruvian territory might be because of several circumstances. First, there has been disproportional population growth and migration to slums or squatter settlements over the last decades (Instituto Nacional de Estadistica e Informatica 2022a, 2022b). The inhabitants of unplanned housing and rural communities have great disadvantages, evidenced by poor living conditions, and are vulnerable to insufficient public service availability. Those areas are only sometimes adequate to install appropriate water supply infrastructure because of the variant topography of the ground and vulnerability to natural hazards. Second, there should be a proper government response to allocate human resources for the administration of public services and the operation and maintenance of deteriorated supply networks. These failures in meeting population needs are reinforced by poor investment to reduce this gap.

Public health implications and recommendations for future studies

Worldwide, more than 2 billion individuals live in countries with water scarcity, in addition to the effects of climate change and excessive population growth, which demand policies on the acceptable use of water. Given this scenario, the Sustainable Development Goals include expanding access to safe water globally. Peru is committed to these goals, specifically to goal 6, which establishes universal and equitable access to safe drinking water at an affordable price for all (United Nations no date). The Joint Monitoring Program – led by the WHO and UNICEF – is focused on the progressive realisation of universal access to drinking water, sanitation and hygiene and decreasing inequalities in service levels by 2030 (WHO/UNICEF no date). Even though this study was not aimed at evaluating water service levels, based on the study results, which indicate inequality and concentration of access to safe drinking water in populations with higher SES, efforts should be emphasised in drinking water programmes to not only guarantee access but also ensure that drinking water meets standards that guarantee its safety.

Access to safe water and health are closely related. On the one hand, water can be contaminated with faecal residues (Usman *et al.* 2018); on the other hand, as pipes run in areas with poor sanitary conditions leading to infiltration of piped water networks, the concentration of residual chlorine could decrease. These facts may trigger the appearance of waterborne diseases such as hepatitis A, dysentery, typhoid, cholera, diarrheal diseases, trachoma and other illnesses, which can affect the population's health status (Centers for Disease Control and Prevention 2020; World Health Organization 2022), particularly among the most vulnerable such as infants, pregnant women, elderly and immunosuppressed individuals (Kumar *et al.* 2022). This point is relevant because acute diarrheal diseases in children are one of the leading causes of infant mortality, particularly in low- and middle-income countries (Levine *et al.* 2020). Indeed, the prevalence of this group of diseases reached 9.4% in Peru in 2021 (Instituto Nacional de Estadistica e Informatica 2022a, 2022b). Therefore, given that the concentration of water chlorine does not provide a complete figure in relation to faecal pollution of water, we suggest running a microbial analysis on samples with residual chlorine concentration (specific pathogen enumeration or faecal indicator bacteria) in future studies.

In contrast, high levels of chlorine in water could cause injury to the respiratory tract, directly, through the effect of chlorine gas (White & Martin 2010) and, indirectly, through the generation of disinfection by-products (Nieuwenhuijsen *et al.* 2000). Therefore, we recommend conducting studies to assess the microbiological characteristics of water and examine the possible health damages of high levels of residual chlorine in water.

The consequences of unsafe water go beyond physiological outcomes, as they can also involve chemical intoxication. In Peru, water often has high concentrations of heavy metals (e.g. arsenic, cadmium and lead) (Piñeiro *et al.* 2021), pesticides, hydrocarbons, and organic chloride compounds, which, if accumulated over time, can poison the population and increase the public health budget (Bernex *et al.* 2017). This health problem is caused by the contamination of rivers and other water sources because of illegal and informal mining activities and oil spills in recent decades in the country (Yusta-García *et al.* 2017).

The intervention of governmental programmes is key to addressing the lack of access to safe water. For instance, the program 'MI AGUA', led by the Ministry of Health, seeks to implement, operate and maintain the intradomicile water treatment system for human consumption. It targets those populations supplied with water from surface watercourses (e.g. rivers, lakes, lakes, irrigation and canals). Additionally, it can be used in disasters or emergencies (Ministerio de Salud 2022). Implementing other programmes aimed at surveilling the concentration of chlorine, heavy metals and other solutes in water is also crucial to prevent waterborne diseases. Finally, these results can be used to establish public policies for supplying safe drinking water to poor households.

Strengths and limitations

This study must be interpreted considering its limitations. First, because of the cross-sectional design of this study, the chlorine concentration is a representative of the moment in which it was measured. Thus, this study does not reflect the variability

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in water chlorination. Second, only the level of chlorine in drinking water was used as an indicator of drinking water quality because free residual chlorine measurements are a partial and indirect indicator of microbial contamination of drinking water. Third, as our outcome definition only evaluated chemical water treatment through chlorine, rather than physical–biological water treatment or others; then, piped water sources where no chlorination is performed, and other safe water sources (e.g. groundwater or water treated with physical–biological treatment) were considered unsafe water. Nevertheless, those sources in which water was stored were sampled and analysed accordingly. Fourth, SaTScan detected only circular-shaped clusters. Thus, some non-high-risk regions could have been included in the clusters (Tango 2021). Fifth, an asset-based measurement of the SES was employed in the absence of direct measurement. However, this approach is valid and has been previously used (McKenzie 2005). In contrast, this study had several strengths. The used database has several observations, which provide it great statistical power and national, departmental and area of residence representativeness. Moreover, the measurement method and the survey process have been standardised and are therefore extrapolable to other middle-income countries. Finally, these results can be used to establish public policies for supplying safe drinking water.

CONCLUSIONS

Approximately one in four Peruvian households has access to safe drinking water, which was mostly concentrated among the wealthier households. Additionally, intra- and interdepartmental inequalities in access to safe drinking water were found, with the presence of several high-risk clusters. Programmes to broaden access to safe water should establish measures to improve access to safe water in locations with low access. Although getting safe water to hard-to-reach territories can be complex, such programmes should focus on providing the tools to make water safe.

FUNDING

Self-funded.

DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories. ENDES database is publicly availables at: https://proyectos.inei.gob.pe/microdatos/.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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