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The geo-spatial perspective of biological, social and environmental determinants of early pregnancy anaemia in rural Sri Lanka: Need for context-specific approaches on prevention

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Abstract

We provide a novel approach to understanding the multiple causations of maternal anaemia in a geospatial context, highlighting how genetics, environment and socioeconomic disparities at the micro-geographical level lead to the inequitable distribution of anaemia. All first-trimester pregnant women registered for the antenatal care programme in Anuradhapura District, Sri Lanka from July to September 2019 were invited to the Rajarata Pregnancy Cohort (RaPCo), which assessed the prevalence of anaemia in early pregnancy. The combination of the prevalence of anaemia and minor haemoglobinopathy-related anaemia (MHA) with the poverty headcount index of the 22 health divisions in the district was investigated using GeoDa spatial K-means clustering. Sociodemographic and economic data at the divisional level were compared between identified clusters. Combining the analysis with the geographical and environmental characteristics of the region, further hypotheses regarding anaemia in this community were formulated. The study included data from 3,137 pregnant women in early pregnancy. The anaemia and MHA prevalence varied from 13.6 to 21.7% and from 2.6% to 5%, respectively. We identified four distinct spatial clusters. The cluster with the highest anaemia prevalence also included high poverty and the highest prevalence of MHA. The clusters had significant differences with regard to ethnic distribution, access to water, sanitation and dietary patterns. Areas supplied by major irrigation projects had significantly low levels of anaemia, probably attributable to internal migration and improved livelihood. It was evident that genetic, socioeconomic and environmental risk factors were grouped at the divisional level, and that their complex interactions make controlling anaemia with blanket interventions unsuccessful. Analysis of the distribution of heterogeneous risk factors at the micro-geospatial level helped identify context-specific approaches to tackle anaemia in pregnancy.

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Introduction

Anaemia is a condition in which the number of red blood cells, or the haemoglobin concentration, is lower than normal leading to inadequate oxygen-carrying capacity. Anaemia in pregnancy is commonly attributed to nutritional aetiologies, the most highlighted being iron deficiency (WHO, 2015). In addition to nutritional deficiencies, haemoglobinopathies and other genetic disorders, chronic blood loss, and chronic diseases also contribute to anaemia (Goonewardene *et al.*, 2012; Owais *et al.,* 2021). Poverty, food insecurity, lack of dietary diversity and poor access to safe water, sanitation and hygiene underpin anaemia in pregnancy (Balarajan *et al.,* 2011; Fite *et al.,* 2021; Hotez, 2008; Ivers& Cullen, 2011; Lebso *et al.*, 2017; Ness *et al.,* 2020; Vilar-Compte *et al.,* 2021). Importantly, these factors vary at national and sub-national levels. For example, Folate deficiencies are high in malaria endemic regions, and a high prevalence of Vitamin B12 deficiency has been reported in the Indian subcontinent and the Caribbean (Chaparro & Suchdev, 2019). South Asians have a high prevalence of minor haemoglobinopathies such as thalassemia and sickle cell disease compared to the rest of the world (Angastiniotis & Modell, 1998; Colah *et al.,* 2010).

One in three reproductive-age females worldwide is anaemic (WHO, 2015). Existing before pregnancy, or occurring *de-novo* during pregnancy, anaemia can take a significant toll on the health of both mother and baby (Alwan & Hamamy, 2015; Brannon & Taylor, 2017; Jwa et al., 2015; Khoigani et al., 2012). In par with United nations' Sustainable Development Goals (SDG), global nutrition targets aim for a 50% reduction in anaemia (WHO, 2014). However, despite considerable efforts, no country is currently on track to achieve this goal. In fact, most countries have shown no progress or even worsening anaemia (di Cesare *et al.,* 2021; Hasan *et al.,* 2022; Kinyoki *et al.,* 2021). Widening underlying inequities due to climate change, humanitarian conflicts and changes in health politics contribute to the agravated anaemia situation in vulnerable populations, such as reproductive-age women (African Development Bank et al., 2004; International Food Policy Research Institute, 2010; World Bank, 2019). Identifying pregnant women who are most vulnerable to anaemia and understanding the micro- and macro-level context in which these risk factors occur is important when looking for strategies to tackle this global health issue. The ecological approach is a new concept where interaction with organisms (here humans) and their environment is utilised to address the multifaceted problem of malnutrition (DeClerck *et al.,* 2011), e.g., by inspection of the associated factors for anaemia with regard to their geospatial distribution.

Geo-spatial data at the sub-national level have emerged as an important source of insight into malnutrition hotspots and inequities, even when the aggregated national-level assessment was optimistic (Osgood-Zimmerman *et al.,* 2018). Several studies on anaemia among pregnant or reproductive-age women have employed geo-spatial analysis methods beyond conventional mapping to understand the patterns of anaemia. The majority of studies used spatial autocorrelation according to Moran's index (Hernández-Vásquez *et al.,* 2017; Jones *et al.,* 2016; Kibret *et al.,* 2019; Agegenehu *et al.,* 2021), while parametric and nonparametric regression models were also used (Belay *et al.,* 2022; Correa-Agudelo *et al.,* 2021; Ogunsakin *et al.,* 2021). These geographical patterns shed light on planning context-specific interventions to deal with the resistant nutritional issues, which would otherwise be masked, and help identify genetic and other risk factor hotspots and associations important in tackling anaemia (Aimone, 2016; Fenta *et al.,* 2021; Kibret *et al.,* 2019; Lai *et al.,* 2017). For example, as shown by Kibret *et al.* (2019), the anaemia prevalence in some states of Ethiopia (Afar and Somali) amount to a severe public health problem, while it is a minor problem in other states (Tigray, Amhara and Addis Ababa). Eastern parts of Ethiopia have been identified as an area of anaemia hotspots for women and children (Kibret *et al.,* 2019; Endris *et al.,* 2021). Further analysis below the state and divisional levels has also shown anaemia clusters, both hotspots and coldspots (Kibret *et al.,* 2019; Correa-Agudelo *et al.,* 2021; Endris *et al.,* 2021). Anaemia prevalence at the sub-national level has been linked with the prevalence of other health conditions, such as malaria (Lover *et al.,* 2014; Correa-Agudelo *et al.,* 2021), HIV (Correa-Agudelo *et al.,* 2021) and stunting (Endris *et al.,* 2021), while environmental factors, such as the content of arsenic (Hopenhayn *et al.,* 2006) and iron (Ahmed *et al.,* 2018) can also play this role.

Sri Lanka is a low- to middle-income country with exceptional maternal care services provided free of charge at the point of delivery (Family Health Bureau Sri Lanka, 2018). Hence almost all maternal health indicators excel compared to countries with similar income levels. Nutritional indicators are the exception and many such issues, including maternal anaemia, remain a problem despite multiple life-course-approach based interventions provided through the national family health programme (Family Health Bureau Sri Lanka, 2018). Anaemia prevalence among the country's pregnant women is around 27% (Family Health Bureau Sri Lanka, 2018). At the sub-national level, the prevalence of maternal anaemia ranges from 14.6% to 62.6% and iron deficiency prevalence varies between 0 to 24.3% among the 26 administrative districts (Jayatissa *et al.,* 2017). An association between anaemia in pregnancy and income level has been shown (Kandauda *et al.,* 2020). More than one-fifth of the anaemia cases among pregnant women in the geographically largest district in Sri Lanka (Anuradhapura) is linked to genetic factors, including minor haemoglobinopathies and membrane disorders (Amarasinghe *et al.,* 2022). Only a few studies in Sri Lanka have been conducted at finer spatial resolutions than the district level to inspect the spatial epidemiological patterns, and these studies are mostly limited to infectious diseases (Karunaweera *et al.,* 2020; Sun *et al.,* 2017). The current study represents an attempt to explain the inequitable distribution of anaemia in pregnancy in Anuradhapura District, Sri Lanka by investigating the geospatial distribution of genetic, environmental and socioeconomic risk factors and their interaction.

Materials and Methods

Study setting

The study was conducted in Sri Lanka's Anuradhapura District, which is 7,179 km^2 large and completely landlocked (Department of Census and Statistics, Sri Lanka, 2018). The district is divided into 22 health units, coinciding with administrative divisions, each under a medical officer of health. Field antenatal care services are provided to all pregnant women free of charge through the Medical Officer of Health (MOH) system (Family Health Bureau Sri Lanka, 2018).

The district has a population of over 0.9 million. Divisions usually have a population of around 50,000, but this varies between 16,617 in Palugaswewa and 7,4370 in Nuwaragampalatha East (NPE). The population density is 128/km^2 (Department of Census and Statistics Sri Lanka, 2018). Figure 1 shows the district's geographical location and the population density of divisions, with the latter distributed outside 1.5 times the interquartile range labelled as outliers. The NPE division contains the only municipal region of the district, i.e. Anuradhapura City. Agricultural activities are the primary source of income forpeople in the district (Department of Census and Statistics Sri Lanka, 2018).

Anuradhapura District is situated in the northern dry planes at an altitude of 92 m and has an annual rainfall between 1,000 to 1,500 mm (Climate of Sri Lanka, 2019.). Since the rainfall is low and mainly limited to the north-eastern monsoons, man-made reservoirs have sustained life and crops in this area since ancient times (Climate of Sri Lanka, 2019). With 2,600 small, medium and large man-made water reservoirs to collect water, a 515 km^2 area in Anuradhapura is covered by water bodies (Department of Census and Statistics Sri Lanka, 2018). Another main water source is the local Mahaweli development programme that diverts water from the wet zone to large reservoirs in the area. Out of the ten Mahaweli systems in Sri Lanka, three cover different parts of Anuradhapura District; Zone H, Zone L and Hurulu Wawa (Mahaweli Authority of Sri Lanka, 2018). In addition, mass resettlements of people originally from the wet zone of the country took place with the establishment of Mahaweli systems.

Main measures and data sources

For the current paper, we have used data obtained from the baseline assessment of the Rajarata Pregnancy Cohort. All first-trimester pregnant women registering for field antenatal care services in their respective MOH areas of the Anuradhapura District during the third quarter of 2019 were invited to participate in this maternal cohort (Agampodi *et al.,* 2020). Participant recruitment was done at special clinics conducted weekly or fortnightly in each MOH area (the total number of clinics conducted was 226). Registration for antenatal care was above 95.1% of estimated pregnancies in the district (Family Health Bureau Sri Lanka, 2018). The recruited population sample included 86% (66%-94% at the divisional level) of the registrants. For the baseline assessment of the cohort, socioeconomic data of the participants were obtained through an interviewer-administered questionnaire. Health records were checked to validate health-related data, such as the reports of thalassemia screening (if any) done previously. The area of residence was verified during the data collection. Dietary habits and frequencies were obtained through a self-completed questionnaire. A full blood count was performed for each participant, and haematological indices were used to guide further etiological assessment of anaemia in this cohort. A <11 g/dL haemoglobin level was the cut-off for anaemia. Participants with microcytic anaemia (expressed as the mean corpuscular volume below 80 cubic µm (=femtoliters, fL) and a red cell count (RCC) $\geq 5 *10^6$/microliter were identified as having minor haemoglobinopathy (Amarasinghe *et al.,* 2021). This algorithm showed a 100% positive predictive value in the preliminary analysis (Amarasinghe *et al.,* 2022). A detailed description of the methodology is provided elsewhere (Amarasinghe *et al.,* 2021).

Poverty headcount and the percentage of agricultural land receiving water from major irrigation projects were obtained from the district statistical handbook 2018 (Statistics Division of District Secretariat Anuradhapura, 2018). Data on rainfall in 2019 was obtained through the department of meteorology. Sources of the data used for analysis are summarised in Table 1.

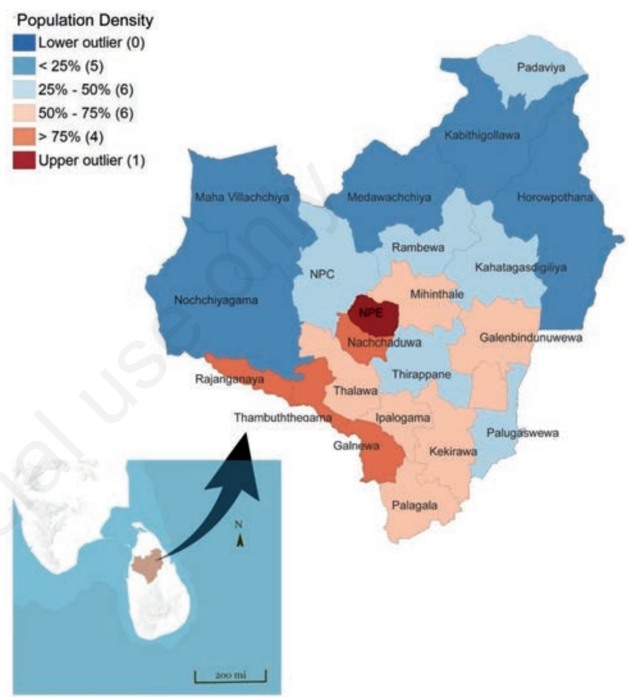

Figure 1. Map of Anuradhapura District, Sri Lanka with population density at the divisional level.

Table 1. Source of data used in the analysis.

Variable	Data Source
Anaemia Prevalence	RaPCo data
Minor haemoglobinopathy-related anaemia prevalence	RaPCo data
Prevalence of moderate and minor anaemia	RaPCo data
BMI categories	RaPCo data
Education level	RaPCo data
Ethnicity	RaPCo data
Income	RaPCo data
Toilet use	RaPCo data
Animal-origin food consumption	RaPCo data
Milk Consumption	RaPCo data
Green-leaf consumption	RaPCo data
Source of water	RaPCo data
Poverty headcount index	District statistical handbook 2018
Percentage* supplied by major irrigation projects	District statistical handbook 2018
Rainfall 2019	Department of Meteorology Sri Lanka

BMI= body mass index; *of agricultural land.

Spatial data analysis

Prevalence of anaemia and minor haemoglobinopathy-related anaemia in each MOH area were mapped by Empirical Bayes (EB) smoothing (https://spatialanalysis.github.io/handsonspatialdata/rate-mapping.html). Rates estimated from small populations may have a large standard error and may erroneously suggest outliers. The EB technique was used to compute a weighted average between the raw rate for each MOH area and the district average, with weights proportional to the underlying at-risk population (the participants). This technique strengthens the crude estimates, and areas with fewer participants and results in bigger rate adjustments than areas with more participants (Maps for Rates or Proportions, 2018). Map classifications were created in such a way that the within-group variance was minimal (natural breaks). K-means clustering was used to identify divisions with similar patterns of distribution of anaemia and its biological and social determinants. Clustering was the preferred approach as it enabled the construction of an overview of how the biological and social determinants modify the anaemia prevalence at the divisional level by clustering the divisions into several groups based on these characteristics.

We performed K-means clustering using GeoDa (Cluster Analysis, 2019) in each MOH division based on three variables: the prevalence of anaemia, the prevalence of minor haemoglobinopathy-related anaemia and the poverty headcount index. Anaemia prevalence was the main variable of the study. Poverty is a variable that resemble many other socio-economic and environmental factors as it is associated with food insecurity, lack of dietary diversity and inadequate access to safe water, hygiene and sanitation, all of which can lead to anaemia through malnutrition, inflammation and infestation (Balarajan *et al.,* 2011; Fite *et al.,* 2021; Hotez, 2008; Ivers and Cullen, 2011; Lebso *et al.,* 2017; Ness *et al.,* 2020; Vilar-Compte *et al.,* 2021). Therefore, we looked at the distribution of poverty headcount at the divisional level, considering it a combined, proxy measure of the above-mentioned poverty variables. A previous analysis of anaemia data in the district had shown that minor haemoglobinopathies, which are caused by genetic determinants, contribute to a significant proportion of all anaemias (Amarasinghe *et al.,* 2022). During observation of collected data and preliminary analysis, the prevalence of minor haemoglobinopathy-related anaemia varied between divisions, where some of which with high anaemia prevalence and low poverty levels had high minor haemoglobinopathy-related anaemia prevalence. Due to these reasons, we considered minor haemoglobinopathy-related anaemia as a main variable in K-means clustering.

Standardised (Z) transformation, Euclidean distance function and K-mean ++ initialization were used for the cluster analysis. Maximum iterations were 1,000 and initialization reruns were 150. Four clusters were obtained. K-means clustering was performed for different values of K and average distances to the centroid across all data points were calculated for each of the K values. The "elbow" point (where the average distance from the centroid suddenly falls) was used to determine the optimal number of clusters.

We triangulated the results of clusters analysis to see if the differences between nutrition level, dietary patterns, access to water and sanitation, income and ethnic distribution agreed with the identified characteristics of the cluster (poverty, anaemia and minor haemoglobinopathy related anaemia levels). Therefore, distribution of mild anaemia (haemoglobin values between 10.0 to 10.9 g/dL) and moderate anaemia (haemoglobin values between 7.0 to 9.9 g/dL), body mass index (BMI) categories, education levels, ethnicities, income levels, dietary patterns, drinking water sources and latrine usage among the study participants were compared between the clusters using chi-square tests in SPSS, version 22 (https://www.ibm.com/support/pages/spss-statistics-220-available-download). It was observed that the anaemia prevalence was lower in areas developed under the Mahaweli scheme. Therefore, the correlation was tested between anaemia prevalence and the percentage of agricultural land supplied by these major irrigation projects using Spearman correlation in SPSS.

Results

Out of the 3,137 first-trimester pregnant women participating in the study, the majority were from Kekirawa (n=245), followed by Galenbindunuwewa (n=206), Nuwaragampalatha Central (n=202) and Medawachchiya (n=192) MOH areas. The least number of participants were from Palugaswewa (n=45).

Prevalence of anaemia and minor haemoglobinopathy-related anaemia

The overall prevalence of anaemia was 14.4% (n=451). When rates were EB-smoothed, the highest and the lowest anaemia prevalence were from Kahatagasdigiliya (21.7%) and Galnewa13.6% (Figure 2).

The highest adjusted prevalence for probable minor haemoglobinopathy-related anaemia was detected in Kahatagasdigiliya (5.0%) and the lowest in Rambawa (2.6%). Generally, MOH areas towards the eastern side of the district were found to be the most affected (Figure 3).

Clusters

Four (4) clusters were observed based on the degree of change in the total within-cluster sum of squares, the between-cluster sum of squares and the ratio of the between-cluster sum of squares to the total sum of squares with the increasing number of generated clusters. The total sum of squares was 117, the total within-cluster

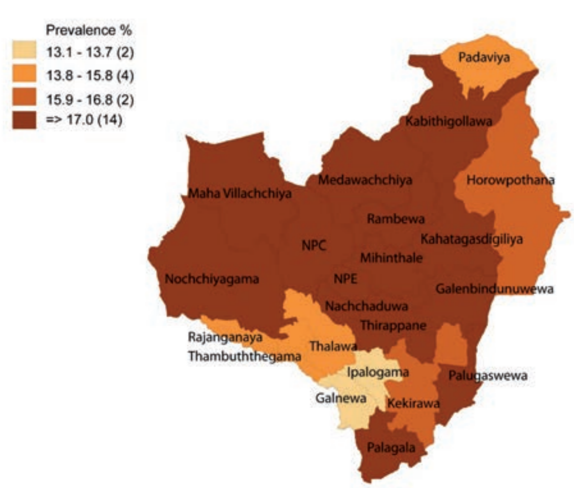

Figure 2. Anaemia prevalence among first-trimester pregnant women in the health divisions of Anuradhapura District, Sri Lanka. Land expansions estimated by empirical Bayes smoothing.

sum of squares was 6.14127, the between-cluster sum of squares was 110.859, and the ratio of between-cluster sum of squares to the total sum of squares was 0.94751 (Table 2).

Figure 4 shows the number of MOH areas per cluster (I, II, III and IV), the population of which were 1,269 (40.8%), 535 (17.2%), 741 (23.8%), and 565 (18.2%), respectively. Observation of the cluster centres showed that the anaemia prevalence was moderate, the minor haemoglobinopathy-related anaemia prevalence low and the poverty headcount moderate in the eight MOH areas belonging to cluster I. In the five MOH areas in cluster II (Medawachchiya, Mahawillachchiya, Kebithigollewa, Galenbindunuwewa and Palugaswewa), anaemia prevalence, poverty and minor haemoglobinopathy-related anaemia were all very high indicating that both factors are responsible for the observed prevalence of anaemia in these areas.

In the five MOH areas belonging to cluster III, poverty was comparatively low, but a moderate prevalence of minor haemoglobinopathy-related anaemia could be observed. The highest percentage of moderate anaemia was noted in this cluster that included Ipalogama, Galnawa, Palagala, Mihinthale and NPE. In cluster IV (Rajanganaya, Thalawa, Thambuththegama and Padaviya), anaemia and minor haemoglobinopathy-related anaemia prevalence were the lowest in the study and the poverty level was also low. The main difference between cluster III and IV was that of the minor haemoglobinopathy prevalence.

Distribution of socio-demographic characteristics between the clusters

Significant differences were observed between the clusters related to ethnic distribution, the severity of anaemia, education levels, income, dietary pattern, sources of drinking water and sanitary toilet usage (Table 3). Cluster II had a significantly higher percentage of participants who only rarely or never consumed meat, fish or eggs and who never or rarely consumed milk. The highest percentage of consumption of bottled or reverse osmosis filtered ((ROF) drinking water was also reported from Cluster II. The lowest usage of sanitary latrines was observed in participants in Cluster III (90.9%) and cluster I (90.5). Cluster IV had the lowest percentage of ethnic Moore/Malay participants.

Cluster association with irrigation supplies

Anaemia prevalence had a reduced association with the increasing percentage of agricultural land supplied by major irrigation projects in each division (Spearman's correlation -0.7, p<0.001). Comparing the map of the cluster membership and areas supplied by the Mahaweli project, it was observed that the anaemia prevalence and that of minor haemoglobinopathy related anaemia were

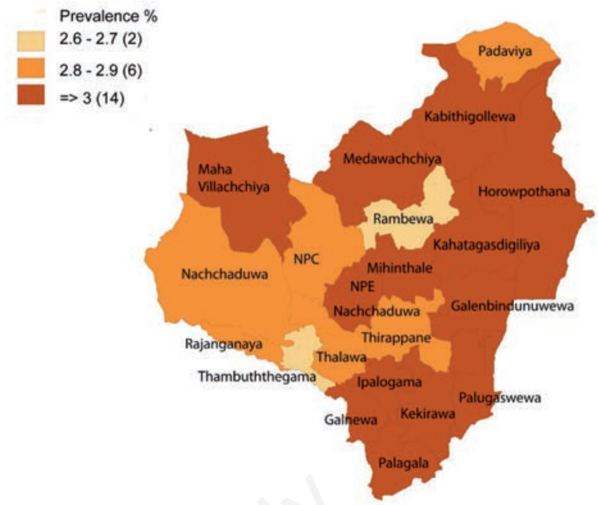

Figure 3. Minor haemoglobinopathy-related anaemia prevalence among first-trimester pregnant women in health divisions of Anuradhapura District, Sri Lanka. Land expansions estimated by empirical Bayes smoothing.

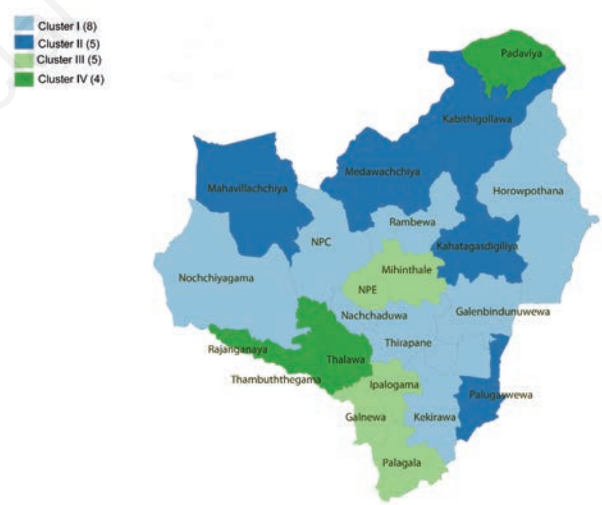

Figure 4. Number of Medical Officer of Health areas per cluster in Anuradhapura District, Sri Lanka.

Table 2. Cluster centres in MOH areas in Anuradhapura District.

Cluster	Anaemia (%)		Minor haemo-globinopathy (%)		Poverty Head index count		Sum of squares*
I	15.73	(Moderate)	1.84	(Low)	7.26	(Moderate)	2.47852
II	19.74	(High)	5.42	(High)	9.02	(High)	1.25775
III	12.56	(Moderate)	3.84	(Moderate)	5.47	(Low)	2.0808
IV	9.75	(Low)	1.38	(Low)	6.96	(Low)	0.324207

*Within cluster.

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lower in areas developed under the Mahaweli scheme, mainly in the L and H zones. Specifically, areas of cluster IV overlapped with zones supplied by the Mahaweli development project (Figure 5).

Discussion

The outcome of cluster analysis resulted in four clusters characterized by a higher presence of mainly poverty (cluster I), mainly minor haemoglobinopathies (cluster III), the double burden of poverty and minor haemoglobinopathies (cluster II) and neither (cluster IV). We were able to determine selected biological, environmental and social factors that associated with the basic characteristics of the different clusters explaining the plausibility of the geo-spatial perspective.

Dietary diversity is known to be associated with better nutritional status (Owais *et al.,* 2021; Zerfu *et al.,* 2016). Especially, inclusion of animal source food can provide higher quantities of quality proteins and better bioavailability of vitamins and minerals including iron. It is also the exhaustive source of vitamin B-12 (Adesogan *et al.,* 2020). Therefore, consumption of food from animal sources is important for prevention of anaemia in women (Adesogan *et al.,* 2020; Nguyen *et al.,* 2018; Owais *et al.,* 2021;). We observed that Cluster II, which had the highest level of poverty, had a significantly higher percentage of participants who do not consume animal-source food. Green leafy vegetable consumption in cluster II was also not significantly high (Table 3), which would otherwise have compensated for the reduced dietary diversity. The association between socioeconomic status and low animal source food consumption has been reported in different populations reflecting poor accessibility, awareness and skills for empowerment on nutrition (Cornelsen *et al.,* 2016; Gebretsadik *et al.,* 2022). Most participants in all four clusters used bottled or ROF water for drinking (Table 3). Chronic kidney disease of unknown aetiology is endemic in this district and often linked to unsafe drinking water (Kafle *et al.,* 2019; Rajapakse *et al.,* 2016). Therefore, people have adopted this source of water for drinking

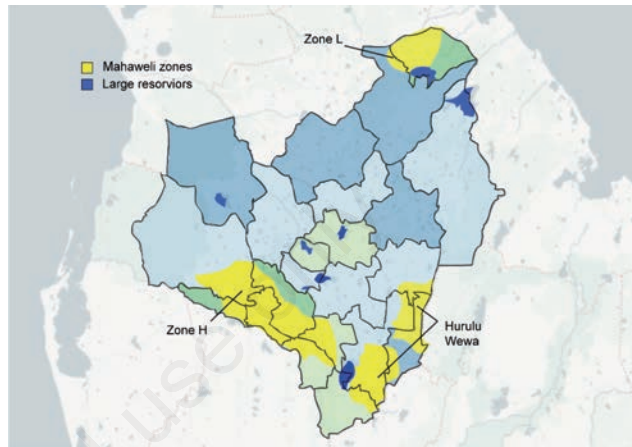

Figure 5. Mahaweli zones in Anuradhapura District, Sri Lanka. Mahaweli = The largest multipurpose development project in Sri Lanka.

Table 3. Characteristics of study participants in the four spatial clusters in Anuradhapura District.

Variable	Result	Cluster I		Cluster II		Cluster III		Cluster IV		X^2
		No.	%	No.	%	No.	%	No.	%	(P)
Severity of anaemia	Mild	144	72.0	67	66.3	63	64.3	51	83.6	7.9
	Moderate	56	28.0	34	33.7	35	35.7	10	16.4	(0.05)
BMI	Underweight	202	15.2	112	19.7	117	14.8	111	18.8	10.1
	Normal	438	32.9	180	31.7	270	34.3	190	32.1	(0.12)
	Overweight/obese	691	51.9	276	48.6	401	50.9	291	49.2	
Education	Up to O/L	879	63.7	356	62.0	425	53.9	353	59.1	21.0
	Beyond O/L	501	36.3	218	38.0	363	46.1	244	40.9	(0.001)
Ethnicity	Moor	203	16.0	70	13.1	95	12.9	5	0.9	96.4
	Other	1066	84.0	456	86.9	640	87.1	560	99.1	(0.001)
Income	Low	291	52.6	137	57.3	126	43.9	133	51.6	1015.0
	High	262	47.4	102	42.7	161	56.1	125	48.0	(0.02)
Toilet use	Water sealed	1257	90.9	525	92.9	711	90.5	569	94.4	14.5
	Pit latrines	116	8.4	36	6.4	72	9.2	28	4.6	(0.03)
	Not used	10	0.7	4	0.7	3	0.4	6	1.0	
Animal origin food consumption	Never/ Rarely	15	3.0	17	7.3	7	2.7	11	4.3	9.3
	More frequently	490	97	216	92.7	255	97.3	242	95.7	(0.03)
Milk Consumption	Never/ Rarely	117	20.7	71	28.5	54	18.4	54	20.5	9.3
	More frequently	448	79.3	178	71.5	240	81.6	210	79.5	(0.03)
Green-leaf consumption	Never/ Rarely	28	4.9	18	7.2	13	4.4	11	4.1	3.2 (0.37)
	More frequently	546	95.1	232	92.8	282	95.6	256	95.9	
Water source	Piped	227	16.4	25	4.4	173	22.0	72	11.9	133.0
	ROF or bottled	1023	74.0	453	80.2	466	59.3	456	75.5	(0.001)
	Other	132	9.6	87	15.4	147	18.7	76	12.6	

BMI= body mass index; O/L=General certificate of education - ordinary level; ROF=Reverse osmosis filtered.

(de Silva, 2020). The highest percentage consuming bottled or ROF drinking water was reported from Cluster II. Consumption of piped water was lowest in Cluster II. Even though it is difficult to draw a conclusion about water scarcity from the limited data available, we could relate this picture to the unavailability of safe drinking water in cluster II. These comparisons provide an overview of the complex social, cultural, economic and food system-related differences between the clusters, which might contribute to their different anaemia prevalence rates.

Cluster IV had the lowest prevalence of minor haemoglobinopathy-related anaemia (Table 2). From the ethnic distribution view point it was noted that cluster IV had a lower percentage of ethnic Moore/Malay participants than the other clusters (Table 3). It has been previously shown that Moore/Malay ethnicity is associated with a higher prevalence of minor haemoglobinopathies (Amarasinghe *et al.,* 2022), which may be linked to their ancestral origins in Central and Southeast Asia, where the genetic mutations for different haemoglobinopathies are higher than elsewhere (Colah *et al.,* 2010; de Silva *et al.,* 2000).

Lower maternal anaemia prevalence in overlapping land areas supplied by the Mahaweli development projects may be due to better food security and more stable income generation due to adequate water supply maintained throughout the year. It signifies that maternal anaemia occurs in a larger contextual frame, which cannot be modified by the health sector alone. Overall development of people's livelihood and securing access to water, food and other needs should be the way forward for further reduction of maternal anaemia in the country. Most of the zones supplied by the Mahaweli project (mainly zones H and L) showed a relatively lower prevalence of minor haemoglobinopathy-related anaemia as well. Mass resettlements on par with the Mahaweli project may explain this observation (Mahaweli Authority of Sri Lanka, 2018). Historically, the northern dry planes of the country, including Anuradhapura, have been severely affected by malaria, which was less endemic in the wet zone (Konradsen *et al.,* 2000). Malaria is known to exert selective pressure on haemoglobin variants in human populations so that the prevalence of variant haemoglobin types is higher in the presence of malaria endemicity (Clegg & Weatherall, 1999). Mahaweli resettlements brought in people from different parts of the country, especially from the wet zone. Therefore, the prevalence of mutations causing minor haemoglobinopathies may be comparatively lower in mass resettlement areas. However, the area covered by Mahaweli zone Huruluweva still has a relatively higher minor haemoglobinopathy-related anaemia prevalence despite resettlements. Differences in the parts of the country from where the majority of the resettlers originated and cultural factors, such as consanguine marriage practices may have led to this observation.

The novel analysis presented here allows targeted approaches for tackling the long-unsolved problem of anaemia in pregnancy. Findings indicate that areas specified by the four clusters need different interventions to prevent maternal anaemia. Poverty alleviation would be the main strategy for improving the well-being of cluster II. Screening to detect heterozygous haemoglobinopathies should be a major focus in clusters II and III. Strategies to help people avoid major haemoglobinopathy (homozygous for the mutation) in their children should also be strengthened in these areas. Currently, the national thalassemia control programme provides a free-of-charge, self-referred screening at specific treatment centres of the country. This programme mainly targets couples awaiting marriage (Premawardhena *et al.,* 2004). However, the only thalassemia screening centre for the Anuradhapura District is situated in Anuradhapura City. Many factors, including the distance, time and monetary costs for visits and stigma associated with the disease, may reduce the uptake of this facility by the individuals in the most affected areas. Therefore, improving access to screening services needs to be considered. Incorporating thalassemia screening into the preconception care programme in these areas would also be beneficial.

The current study demonstrates a depth of observation making it possible to appropriately tackle anaemia, a major maternal health problem, which is often mismanaged by just adhering to mass routine strategies, such as oral iron supplementation and nutritional education. In an era where achieving the SDG targets are threatened due to inflation of inequities amidst a global pandemic and ensuing financial crisis, health and developmental authorities need to be vigilant with regard to vulnerable populations. It is high time for global and local health and development authorities to inspect populations through macro lenses, use novel methods of analysis that encounter the multifactorial causation of phenomena and utilise available resources in the most cost-effective targeted interventions to obtain sustainable development.

The limitation of the present study was mainly that we used subpopulation-level data to compare the clusters, which makes the analysis vulnerable to ecological fallacy. However, the results still provides a useful overview of the complex social, cultural, economic and food -related differences between the clusters, which most probably contributed to different anaemia prevalence rates between them. Further quantitative and qualitative analysis to identify how they are connected to anaemia is recommended.

Conclusions

Studying the geospatial distribution of anaemia in pregnancy and its associations reveal the clustering of genetic, socioeconomic and environmental factors shedding light on probable interventions that could be beneficial in controlling, even preventing the intergenerational transfer of this long-standing health condition. In communities where anaemia in vulnerable population groups are evidently caused by heterogeneous aetiologies, analysing genetic, socioeconomic and environmental factors with a geospatial point of view would be helpful to identify focused control strategies.

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