



Geochemical variation between surface and subsurface soils and relationship to chronic kidney disease in North Central Province, Sri Lanka

Sansfica. M. Young · Indeewari. A. Perera · H. Ishiga

Received: 3 March 2018 / Accepted: 22 April 2021
© The Author(s), under exclusive licence to Springer Nature B.V. 2021

Abstract Chronic kidney disease (CKD) in the North Central Province (NCP), Sri Lanka, is becoming a major cause of national burden with high mortality and morbidity. The origins of these kidney diseases are unknown, and the exact aetiology is not yet understood. Therefore, as an attempt to understand the effect of soil characteristics towards the disease, soil of surface ($n = 25$) and subsurface (50 cm depth, $n = 25$ of each) was collected from Horowpothana (HWP $n = 50$), Kabithigollawa (KBG $n = 50$), Medawachchiya (MWC $n = 50$) and Padaviya (PDW $n = 50$) of the NCP, where the highest number of patients is recorded. The soil samples were analysed using X-ray fluorescence for 22 major and trace elements, and the pH, electrical conductivity and oxygen reduction

potential (ORP) for each sample were measured. The soil of all four villages mainly shows basic conditions. The high concentration of heavy mineral signatures in Horowpothana, Kabithigollawa, Padaviya and Medawachchiya could relate to high CKD patients in these four areas. The 50-cm soils of all four areas are in oxidized condition, while surface soil is in the anoxic condition. High fluctuation between surface and 50 cm may indicate high mobility of ions. According to the current study, P, F^- and Fe_2O_3 ion could easily be mobilized into the groundwater of the area and thereby be related to the highest recorded CKD patients in these areas. Thus, as for the current study the heavy metals and elements that indicate the variations which causes health issues are Fe_2O_3 , Pb, Zn, Cr, F^- , Ti, Cu, Ni, V and Zr.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10653-021-00961-8>.

Sansfica. M. Young (✉)
Department of Environmental Technology, Faculty of
Technology, University of Colombo, Colombo, Sri Lanka
e-mail: sansfica@et.cmb.ac.lk

Indeewari. A. Perera
Department of Physical Sciences, Faculty of Applied
Sciences, Rajarata University of Sri Lanka, Mihinthale,
Sri Lanka

H. Ishiga
Department of Earth Science, Shimane University,
Matsue 690-8504, Japan

Keywords Chronic kidney disease · Heavy metal · Heavy mineral · Mobility · Soil

Introduction

In Sri Lanka, CKD is widespread and has currently become one of the most burning environmental-related health issues (Chandrajith et al., 2011a, b; Gunatilake et al., 2014; Wimalawansa, 2016). The potential causes for prevalence of CKD identified by various studies are heavy metals (Perera et al., 2020;

Wanigasuriya et al., 2008), fluoride (Ileperuma et al., 2000; Young et al., 2010), cyanobacterial and algae toxins (Wanigasuriya et al., 2008), agrochemicals such as phosphate or glyphosate (Jayasumana et al., 2014) and high salinity and iconicity of water (Jayasekera et al., 2012). Furthermore, the unhealthy habits such as drinking water from paddy fields, overusing agrochemicals, consuming very less water than the daily required amount (avg 2L), heavy use of illegally prepared alcohol and ayurvedic (Traditional) medicine, which attained by the residents of the North Central Province (NCP), over the past four decades also, are identified as causes of CKD (Wimalawansa, 2016). CKD is now geographically demarcated and continuously spreading into areas adjacent to the NCP and distant regions, such as the southern part of the Northern Province, northern parts of the Hambantota and Badulla district, in Sri Lanka (Ileperuma et al., 2000).

In NCP, agriculture is the main occupation and the major source of income of the people (Gunatilake et al. 2014). The most common cultivations are paddy, maize and vegetables. The farmers' main concern is to obtain the maximum crop yield and a large profit at the end. Therefore, excessive amounts of agrochemicals (fertilizers, pesticides, etc.) and organic amendments are added as inputs to this soil by farmers without considering the recommended doses. After long-term land application of fertilizer and agrochemicals, the content of impurities significantly increases in soil and water. As a result of this, soils of NCP have a high tendency to be contaminated due to accumulation of heavy metals and metalloids. The application of fertilizer in the hill countries may also cause accumulation of heavy metals in the NCP soil due to the eventual drains of fertilizer via Mahaweli River into reservoirs in the Rajarata area (Wimalawansa & Wimalawansa, 2014). Certain elements occur naturally as a component of minerals in soil, but it may be toxic at exceeded concentrations than the recommended levels. Heavy minerals are commonly used to extract information on both provenance and sedimentological processes and to look for anomalies (Garzanti & Andò, 2019; Jayawardana et al., 2014). The most common heavy metals and metalloids associated with CKD in Sri Lanka were studied currently and has been predicted to be associated with Cd, Pb, As, Hg, Ni, Zn, V, Sb, Cu and Se (Chandrajith et al., 2012; Jayawardana et al., 2014). Therefore, the analysis of

heavy metal, metalloids and trace metal concentrations in soils and identifying the sources, which could be causative to the CKD, are essential to implement control measures to protect the soil.

Study area

The four studied villages are lying in the Wannī complex (Cooray, 1984) where the dominant rock types are granitoid gneisses, migmatites, granites and scattered metasediments (garnet–cordierite gneisses, meta-quartzites) as well as charnockitic rocks (Cooray, 1984; Paul & Emmnem, 1990). Soil derives from these rocks that cover the landscape in Sri Lanka and they are usually between 40 and 150 cm deep in most places and the top soil is not deeper than 15 cm (Thenabadu, 1988). The main soil group of the studied area is well-drained reddish brown earth, associated with low humic gley soil (Chandrajith et al., 2005). The 60–80% reddish brown earth soil with moderate gravel is associated with 15–35% of low humic gley soil and is seen in this region (De Alwis & Panabokke, 1972). These soils occur in a catenary sequence and occupy the crest and the well-drained upper and mid-slopes of the undulating landscapes (Cooray, 1984). The colour of the surface is reddish brown when dry and turns to dark reddish brown when moist. A subsoil horizon with a high proportion of quartz gravel is present, and the depth to the gravel layer is variable (Panabokke, 1996). Soils are extremely hard when dry and friable to firm when moist. Soil reaction is slightly acidic to neutral (Thenabadu, 1988). Base saturation is 60–80%. Soils are low in P but are reasonably high in K (Moorman & Panabokke, 1961). They have a low water-holding capacity with a rapid release of soil moisture at low tensions (Wickramasinghe et al., 2004). The organic carbon content is very low (1–2%). This study was carried out in the Divisional secretariat of Kabithigollawa (KBG), Medawachchiya (MWC), Horowpothana (HWP) and Padaviya (PDW) in Anuradhapura administrative district of the North Central Province (Fig. 1). The agricultural and non-agricultural lands (forests and home lands) are dominant land types of these areas.

Understanding the present concentrations of elements in soils is essential to identify the sources and trends of the contamination of soils. Therefore, the aim of this study was to determine the elemental concentrations in the soil of four villages and establish the

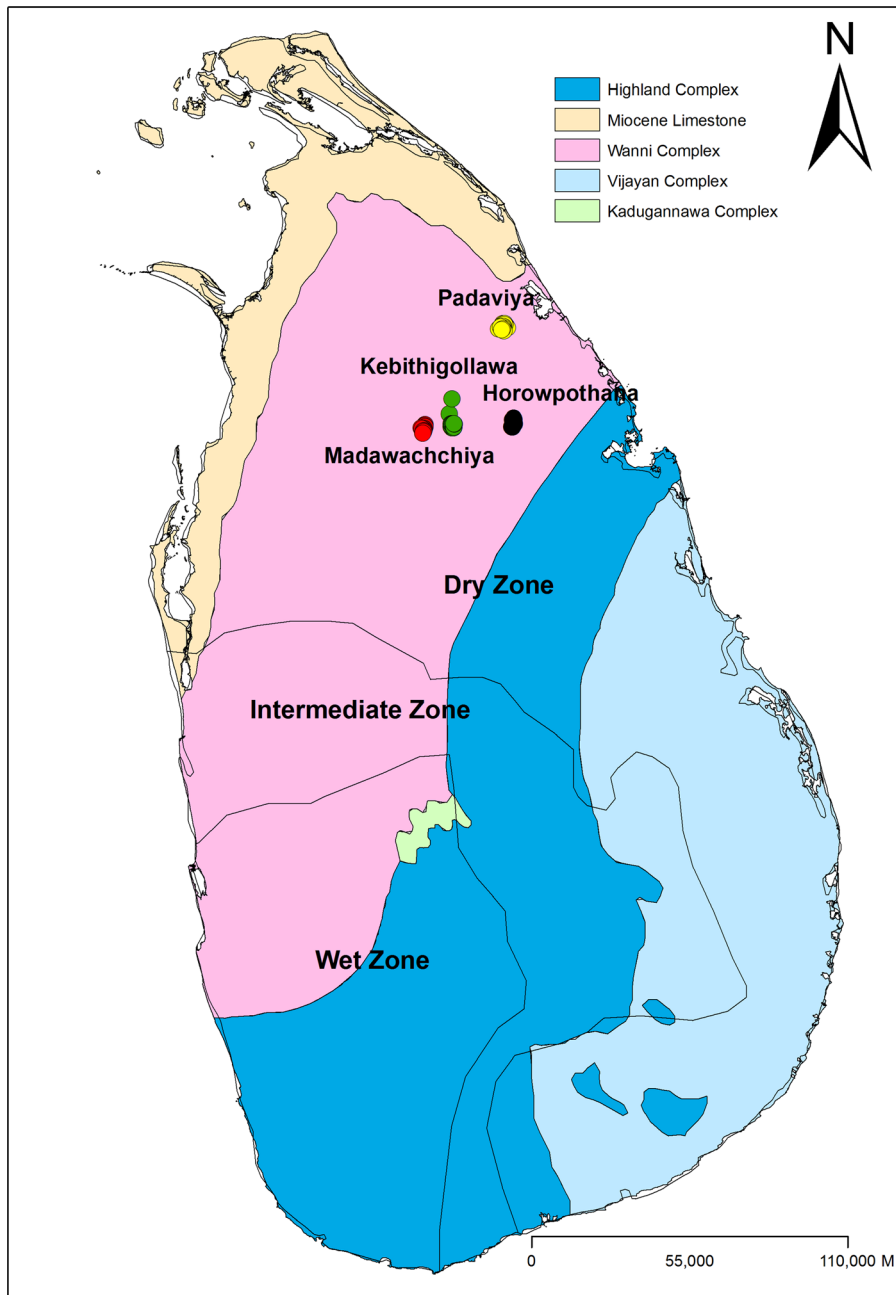


Fig. 1 Map showing the sampling locations

relationships between elemental concentrations and soil properties and assess the soil environment of four villages and their relationships. The most important objective of this study was to build the geophysical relationship between surface and subsurface soils of these CKD-affected study areas and identify the mobility of the elements through the vertical soil

profile and recognize the abundance of harmful elements in the surface and subsurface soil, since to date previous related studies carried out in relation to this topic have not conceded the soil profiles and related it with CKD in the NCP.

Methodology

In order to select the sampling sites, a preliminary investigation was carried out focusing on the distribution of patients suffering from CKD in the dry zone. The government agent and the agricultural officer of each area were consulted, and the households where the patients live were recorded. Selecting the locations was done with the guidance of the respective government agent. The topographical maps of 1:50,000 scale (map number 30-Kala Oya, map number 31-Anuradhapura), available at Survey Department, Sri Lanka, were used to identify the selected area and its features.

Soil samples were collected from 100 randomly selected locations (25 locations from each area) from the households where patients live, during the dry period from March to April 2015 from Horowpothana, Medawachchiya, Kabithigollawa and Padaviya. Soil samples were taken from the surface (within 1–6 cm) and 50 cm below (Fig. 2) at each location (total $n = 200$). The coordinates of the sampling locations obtained from the global positioning system (GPS) and were used for plotting the sample locations (Fig. 1). Soils in the agricultural and non-agricultural fields, which are mainly closer to the wells used for domestic purposes and less-disturbed home lands, were collected. Sampling locations were decided by discussing with the agricultural officer of the area and selected the area that had the highest number of CKD patients. The samples collected were transferred into zip-locked bags and sealed in the field. The samples were transported in double-sealed bags to Shimane University Japan, after drying for 120 °C in an oven.



Fig. 2 The sampled surface and 50 cm soil

Thereafter, approximately 100 g of each sample was dried in an oven at 160 °C for 48 h since volatile components and some of the organic matter and gases that may be released out from organic matter may break the vacuum of the XRF. The dried samples were sieved by 2-mm sieve and then ground for 20 min in an automatic agate mortar and pestle grinder. Powdered samples ($< 63 \mu\text{m}$) were compressed into briquettes under a force of 200 KN for 60 s. The briquettes were then analysed for 23 major and trace elements using powder diffraction method as for Kimura & Yamada, 1996. The selected elements and major oxides such as TiO_2 , Fe_2O_3 , MnO , CaO , P_2O_5 , As, Pb, Zn, Cu Ni, Cr, V, Sr, Y, Nb, Zr, Th, Sc F, Br, Cl, I and total sulphur (TS) were analysed using X-ray fluorescence spectrometry using a Rigaku RIX 2000 spectrometer equipped with an Rh-anode tube at the Department of Geoscience in Shimane University, Japan. Relative average error for these elements is less than $\pm 10\%$. The instrumental conditions, interference corrections and calibration used were those described by Kimura & Yamada, 1996. Primary calibration was made using the same disks from that study, including both international rock standards, synthetic mixes, and standards with elemental ranges extended by standard addition. These standards thus had elemental ranges spanning that expected in most geological situations. Overlap corrections were applied for significant spectral interferences among the trace elements, as specified by Kimura & Yamada, 1996. During routine analysis, the primary calibration was verified by analysis and cross-calibration of nine Geological Survey of Japan rock standards spanning the compositional range from gabbro to granite. When values where abundances are $< 10 \text{ mg/kg}$ are excluded, the range of two-sigma values for the trace elements falls to a maximum of 12.7% relative, and for half of the analysed elements (Nb, Ni, Pb, Rb, Sr, Y, Zr) the precision is better than 5%.

In the laboratory at Rajarata University of Sri Lanka, 10 g of each soil sample was dispersed in 20 mL of distilled water (1:2 ratio) and stirred the soil suspension by swirling the test tube slightly while obtaining the measurements. Horiba pH/ conductivity meter D-54 was used for measuring pH, conductivity, temperature and ORP separately of the soils. The relevant probe was used to measure each of the parameters.

The software used for statistical data analysis was Minitab 14, SPSS 16 and Microsoft Office Excel. ArcGIS 9.2 was used to prepare all maps used for the study. Discrimination diagrams and ratio plots were used to interpret the data.

Results

Physical parameters

The soil pH of MWC and KBG varies within 5–9, whereas in HWP and PDW pH varies within 7–8.5 (Fig. 3). In the Horowpothana, soil samples up to

sample number 13 both surface and 50-cm sample have similar pH or 50-cm samples have slightly lower pH (Fig. 3a). After sample number 14, the pH of the 50 cm is much higher than surface samples (Fig. 3a). In the samples of Kabithigollawa and Medawachchiya, the variation of pH is very high (Fig. 3b and c). Medawachchiya samples 16–25 of show higher pH values of surface than 50 cm (Fig. 3c). In the Padaviya area, the pH has a slight variation between the surface and 50-cm samples (Fig. 3d).

All samples of Horowpothana show higher ORP in 50-cm samples (Fig. 4a). The ORP of almost all the locations of HWP surface and 50 cm varies within 60–90 mV except HWP1 that has (-) 10 mV (Fig. 4a).

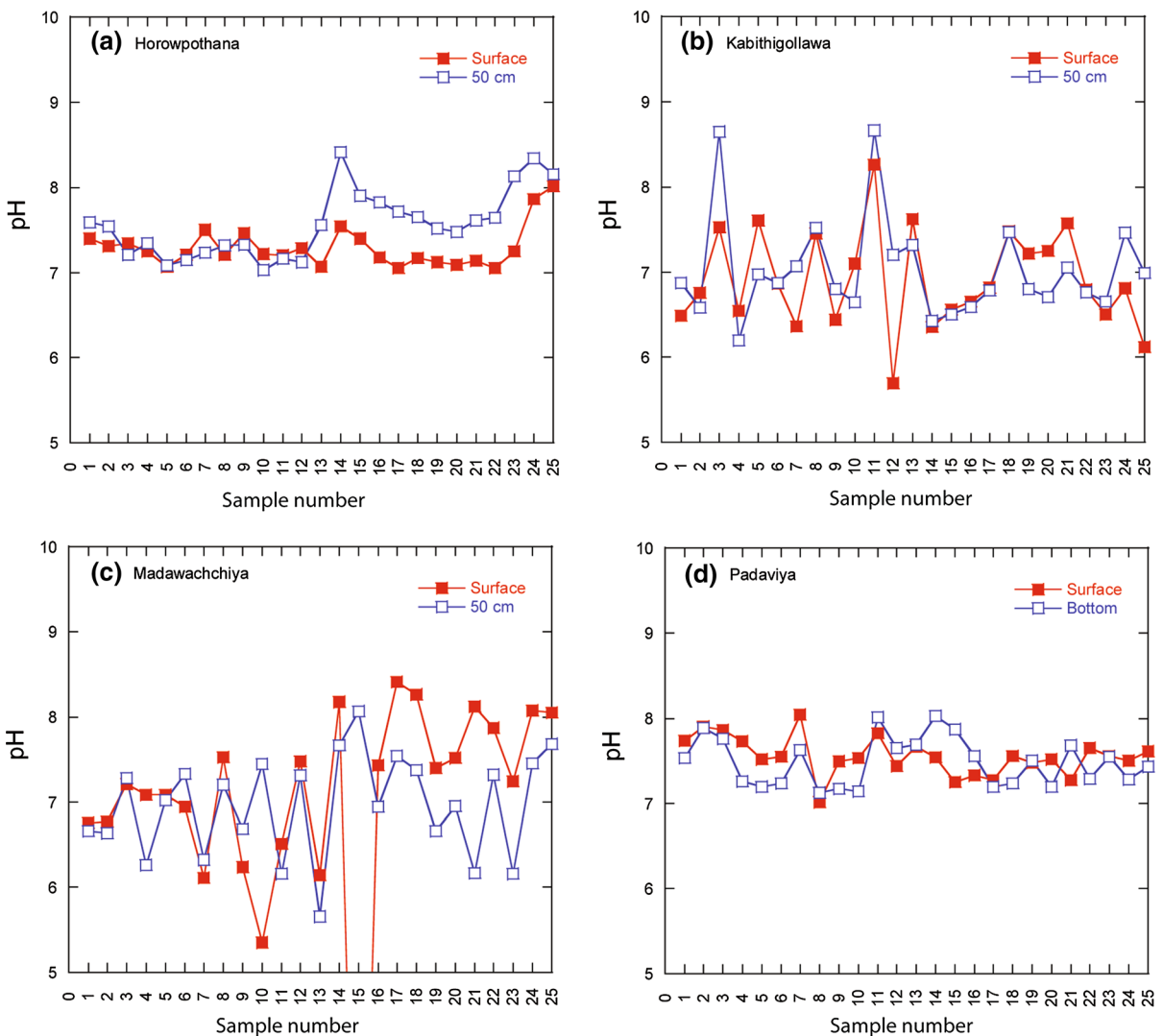


Fig. 3 The pH variation of the surface and 50 cm soil of the four areas

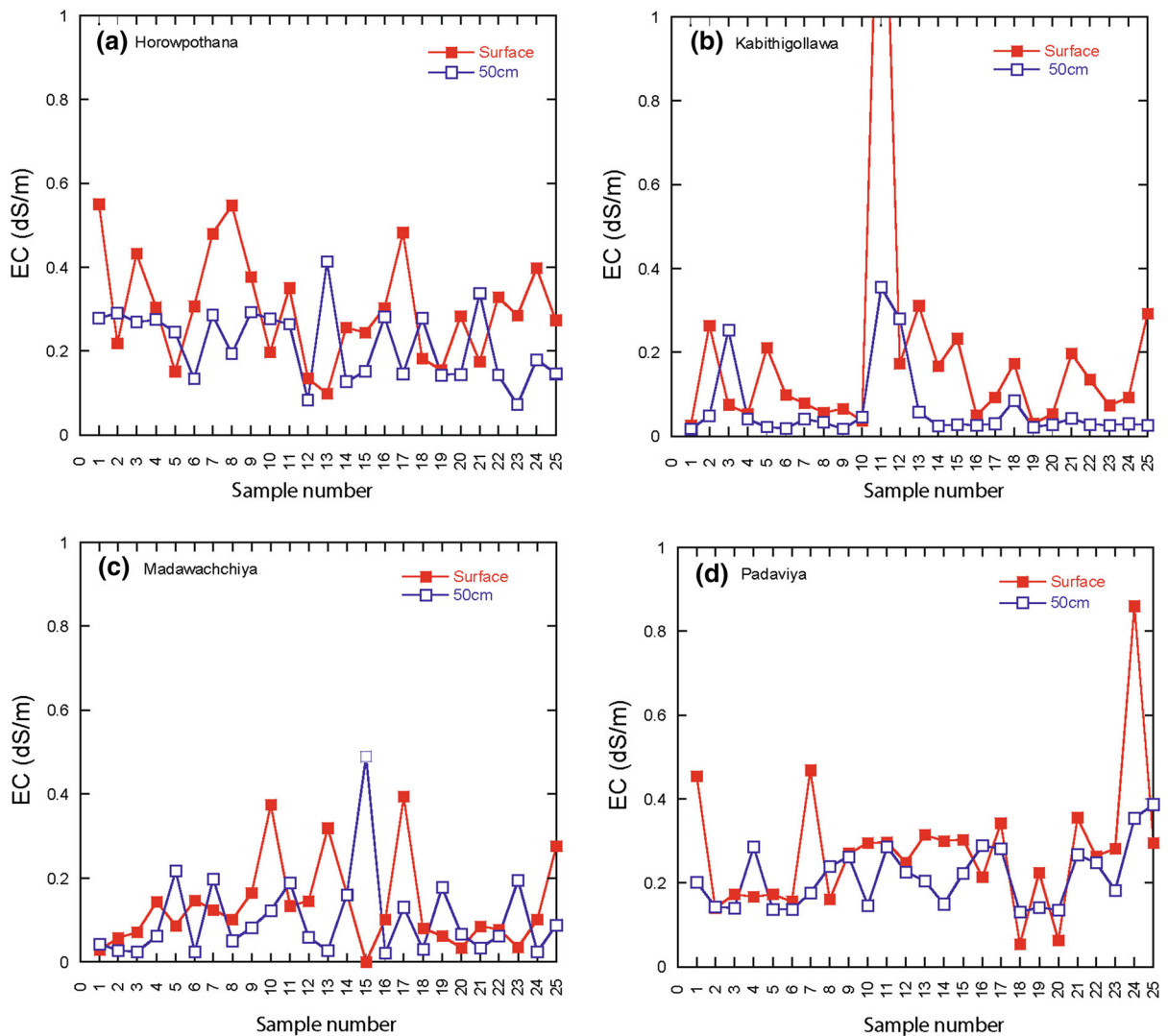


Fig. 4 The electrical conductivity (EC) variation of the surface and 50 cm soil of the four areas

The ORP of 50-cm soil has high positive values than surface soil in almost all the locations of KBG and MWC paddy-cultivated lands (Fig. 4b and c). The highest ORP values acquired were from agricultural land and are in KBG-25, which was 221.5 mV in the surface sample and MWC-14 non-agricultural land 50-cm sample of 210 mV. The PDW surface samples of PDW1 to 4 and 50-cm samples of PDW 11 to 14 show negative ORP values, whereas the other surface and 50 cm vary within 6–62 mV (Fig. 4d). Horowpothana and Padaviya samples do not show high variation in ORP with surface and 50 cm, while Kabithigollawa and Medawachchiya show fluctuations that are not very high (Fig. 4).

In almost all the samples, the EC is higher in the surface samples (Fig. 5 a, b, c, d). The EC of almost all the locations of HWP, KBG, MWC and PDW varies within 0.01 to 0.05 dS/m, while surface samples of KBG-11 and PDW-24 show the highest EC values of 0.164 dS/m and 0.086 dS/m, respectively (Fig. 5 a, b, c, d).

Elemental concentration variation in surface samples

All minimum, maximum, mean and the standard deviation values of all the analysed elements of surface and 50 cm for all four study areas are given

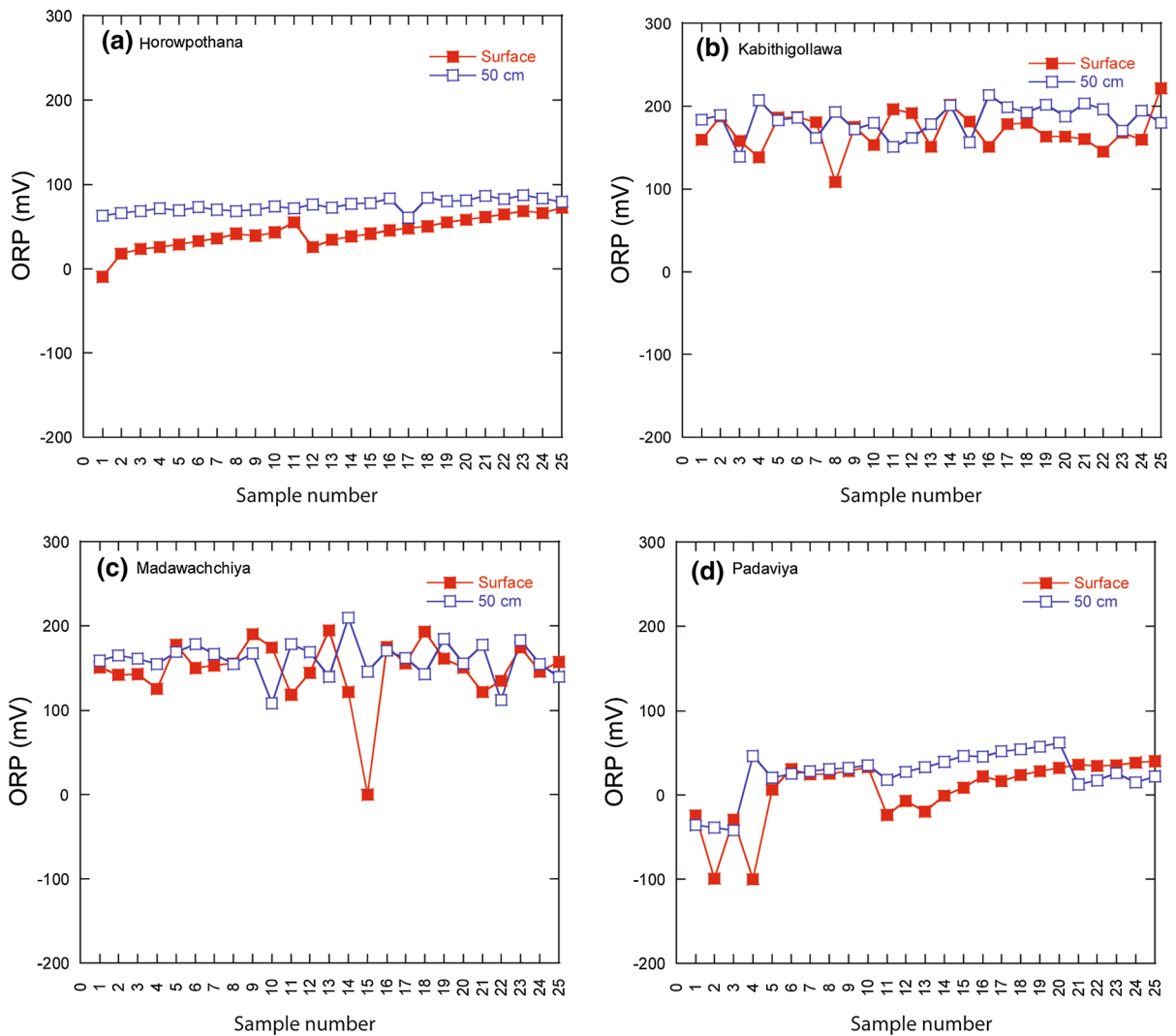


Fig. 5 The oxygen reduction potential (ORP) variation of the surface and 50 cm soil of the four areas

in Table 1. The statistical values have been obtained by descriptive statistical methods. KBG- 9 sample shows higher As concentration (12 mg/kg) than upper continental crust (UCC) value (5 mg/kg), while all the other surface samples lie below the UCC value. The KBG-9 and HWP-16 surface samples show a higher concentration of Pb (232 mg/kg and 35 mg/kg, respectively) than UCC of 20 mg/kg. Out of the samples, 32% of KBG and 20% of PDW samples exceeded the UCC value of Zn (71 mg/kg).

The Cu content exceeded by 28% for KBG, 32% for MWC, 56% for HWP and 52% for PDW than UCC of 25 mg/kg. The Ni concentration of KBG, MWC, HWP and PDW exceeded by 28%, 16%, 24% and 60%

of the samples, respectively, than the UCC value, which is 20 mg/kg. Out of the samples, KBG 44%, MWC 36% and PDW 8% exceeded the UCC value of Sr, which is 350 mg/kg. The Y concentration of UCC (22 mg/kg) exceeded in KBG is 4%, MWC 24% and PDW 12%. The Nb UCC concentration (25 mg/kg) was exceeded only in KBG by 16% and MWC by 52%. Out of the samples in KBG 12%, MWC 20% and HWP 56% was exceeded in Th than UCC (11 mg/kg). The Sc UCC concentration (11 mg/kg) exceeded in samples of KBG by 48%, MWC 40%, HWP 32% and PDW 92%.

The elements that show high standard deviation (Table 1) are as follows: for Horowpothana, Zn (15.5),

Table 1 Summary of the elemental concentrations for surface and 50 cm soils of Horowpothana, Kabithigollawa, Medawachchiya and Padawiya

	As	Pb	Zn	Cu	Ni	Cr	V	Sr	Y	Nb	Zr	Th	Sc	TS	F	Br	I
<i>(mg/kg)</i>																	
<i>Horowpothana Surface (n = 25)</i>																	
Min	0.5	4.7	15.5	8.2	6.7	66.5	71.7	43.4	3.0	4.4	152.6	6.3	3.1	246.7	2.1	2.1	2.1
Max	3.6	34.6	76.5	96.7	59.0	374.0	445.2	262.4	30.1	24.9	889.7	28.6	17.7	1731.0	203.0	18.7	18.7
Mean	2.5	14.2	43.9	40.2	23.6	145.6	233.0	145.2	21.2	13.1	608.5	14.8	10.6	595.7	104.2	4.1	4.1
Std Div	0.5	4.7	15.5	28.4	15.0	85.1	71.7	43.4	3.0	4.4	152.6	6.3	3.9	246.7	58.1	3.5	3.5
<i>Horowpothana 50 cm (n = 25)</i>																	
Min	1.8	9.8	23.6	12.4	14.6	74.2	136.6	53.9	0.0	9.0	424.8	9.7	4.9	402.0	25.0	25.0	25.0
Max	3.3	18.0	68.1	133.9	59.1	249.4	487.6	266.7	34.4	25.3	880.2	23.9	20.7	1039.0	280.0	280.0	280.0
Mean	2.5	13.0	46.1	58.6	30.8	122.8	267.1	132.0	23.9	14.6	613.0	15.4	12.7	499.6	141.8	141.8	141.8
Std Div	0.4	2.0	12.3	39.5	11.2	47.6	77.9	47.6	6.1	4.4	113.8	4.4	3.8	125.4	82.5	82.5	82.5
<i>Kebithigollawa Surface (n = 25)</i>																	
Min	1.2	9.4	20.6	5.3	4.8	22.7	104.7	69.0	6.2	11.5	274.9	4.6	1.0	363.0	0.0	2.1	2.1
Max	11.5	232.4	96.7	52.8	66.3	243.2	339.8	475.6	23.4	32.7	688.2	33.5	18.3	1098.0	275.0	8.7	8.7
Mean	2.7	27.1	49.0	21.8	26.0	121.2	222.2	333.3	17.6	20.2	454.5	10.8	10.9	583.7	85.4	3.7	3.7
Std Div	1.9	44.0	16.8	11.4	15.9	45.8	56.5	88.9	3.4	5.7	110.9	5.6	4.2	174.2	74.4	1.7	1.7
<i>Kebithigollawa 50 cm (n = 25)</i>																	
Min	1.4	6.9	4.1	7.1	4.1	24.1	65.6	44.3	9.5	8.9	286.0	4.4	0.2	357.0	0.0	2.3	2.3
Max	3.1	30.9	73.5	44.8	72.6	304.0	339.9	460.6	23.7	31.7	567.2	25.1	19.0	539.0	301.0	5.3	5.3
Mean	2.4	16.2	42.5	26.8	38.3	143.9	227.6	294.7	18.4	18.1	428.5	9.3	12.3	448.4	79.9	3.7	3.7
Std Div	0.4	4.6	15.3	9.7	17.1	56.7	61.1	102.0	3.6	5.8	83.0	5.1	4.7	51.9	83.5	0.8	0.8
<i>Madawachchiya Surface (n = 25)</i>																	
Min	1.1	10.1	17.5	11.2	4.7	62.7	172.5	62.2	9.5	12.2	137.5	2.8	4.4	415.0	24.0	1.8	1.8
Max	2.8	19.3	103.6	35.2	41.6	189.8	483.0	634.5	23.9	45.7	758.3	22.8	19.6	758.0	344.0	5.8	5.8
Mean	2.2	14.4	48.9	21.6	19.7	114.4	283.5	301.7	17.0	25.3	449.8	8.9	11.9	516.3	124.8	3.1	3.1
Std Div	0.3	2.4	18.7	6.3	8.8	34.8	70.2	127.5	3.5	7.9	138.3	5.0	3.8	71.9	73.5	0.8	0.8
<i>Madawachchiya 50 cm (n = 25)</i>																	
Min	1.3	8.6	23.7	17.9	13.8	75.8	197.5	50.9	11.4	10.9	183.1	2.9	8.7	355.0	4.4	2.1	2.1
Max	3.0	17.6	115.8	40.0	49.6	214.9	428.6	560.1	27.4	34.2	646.3	17.3	19.4	591.0	247.0	7.0	7.0
Mean	2.2	13.7	46.8	27.9	30.4	131.5	283.6	264.8	18.2	22.2	417.4	8.5	13.2	460.7	90.1	3.8	3.8
Std Div	0.5	2.5	19.0	5.3	8.4	36.7	58.4	108.7	3.9	5.7	99.0	3.5	3.0	61.2	73.1	1.1	1.1
<i>Padawiya Surface (n = 25)</i>																	
Min	1.0	9.0	20.5	9.0	5.1	54.7	139.2	159.5	11.5	9.8	164.4	1.0	8.9	504.0	16.0	2.5	2.5

Table 1 continued

As	Pb	Zn	Cu	Ni	Cr	V	Sr	Y	Nb	Zr	Th	Sc	TS	F	Br	I
Max	3.1	17.6	108.1	55.6	44.1	206.5	445.1	491.8	27.0	19.4	476.3	6.3	25.9	727.0	319.0	9.1
Mean	2.0	12.2	57.9	33.7	21.5	116.3	259.9	286.3	17.4	14.6	355.6	3.5	17.5	593.0	145.9	3.8
Std Div	0.5	2.8	22.1	14.0	8.5	31.9	71.1	69.4	3.9	2.7	72.3	1.4	4.5	75.8	95.0	1.3
<i>Padaviya 50 cm (n = 25)</i>																
Min	1.4	8.5	28.6	15.8	19.2	44.4	143.3	145.5	15.5	10.8	146.6	1.5	3.3	352.0	2.4	2.2
Max	2.7	19.5	79.3	64.2	69.6	183.1	397.1	581.9	33.6	22.2	463.3	10.0	26.1	732.0	329.0	13.5
Mean	2.2	12.2	59.6	40.4	33.6	132.2	291.9	309.0	19.9	14.6	328.9	3.9	20.4	536.9	100.2	4.6
Std Div	0.4	2.6	11.4	12.6	10.8	33.9	66.3	93.0	4.1	2.8	65.3	1.8	5.3	83.2	99.1	2.0
UCC	10.00	20.00	71.00	25.00	20.00	35.00	60.00	350.00	22.00	25.00	190.00	10.70	11.00		557.00	1.60
TiO ₂	Fe ₂ O ₃	MnO	CaO	P ₂ O ₅	Th/Sc	Zr/Sc	Cr/V	Y/Ni	pH	EC (µs/cm)	ORP (mV)	T °C				
(Wt%)																
<i>Horowpothana Surface (n = 25)</i>																
Min	0.5	1.8	0.0	0.4	0.6	32.4	0.3	0.3	7.1	100.0	-10.0	1.2				
Max	2.6	9.6	0.2	2.7	9.0	242.2	1.9	2.8	8.0	551.0	72.0	27.7				
Mean	1.3	6.0	0.1	1.3	1.7	69.9	0.6	1.2	7.3	300.7	42.4	26.0				
Std Div	0.5	1.8	0.0	0.4	1.6	50.4	0.3	0.6	0.2	127.3	18.5	1.2				
<i>Horowpothana 50 cm (n = 25)</i>																
Min	0.8	4.3	0.0	0.7	0.6	26.2	0.3	0.0	7.0	72.8	60.0	25.0				
Max	2.5	13.4	0.2	2.4	3.5	126.1	1.1	1.4	8.4	413.0	87.0	27.2				
Mean	1.4	7.9	0.1	1.1	1.3	53.4	0.5	0.9	7.6	218.3	74.8	25.8				
Std Div	0.5	2.0	0.0	0.3	0.7	22.4	0.2	0.3	0.4	86.4	7.3	0.9				
<i>Kebithigollawa Surface (n = 25)</i>																
Min	1.0	1.2	0.0	0.8	0.4	17.3	0.2	0.3	5.7	27.6	108.0	28.9				
Max	2.3	9.4	0.2	2.5	6.9	471.0	1.2	2.3	8.3	1643.5	221.5	30.6				
Mean	1.6	5.6	0.1	1.7	1.4	62.5	0.6	0.9	6.9	187.6	169.7	29.3				
Std Div	0.4	1.7	0.0	0.4	1.6	87.6	0.2	0.5	0.6	315.0	23.4	0.4				
<i>Kebithigollawa 50 cm (n = 25)</i>																
Min	0.8	0.6	0.0	0.6	0.3	21.5	0.3	0.2	6.2	17.1	139.0	27.5				
Max	2.1	9.1	0.2	2.1	24.5	1804.0	1.7	2.4	8.7	356.0	213.5	29.1				
Mean	1.5	6.8	0.1	1.3	1.9	108.6	0.7	0.6	7.0	65.4	183.2	28.4				
Std Div	0.4	1.7	0.0	0.3	4.8	353.6	0.3	0.5	0.6	89.7	18.6	0.4				
<i>Madawachhiya Surface (n = 25)</i>																

Table 1 continued

	TiO ₂	Fe ₂ O ₃	MnO	CaO	P ₂ O ₅	Th/Sc	Zr/Sc	Cr/V	Y/Ni	pH	EC (μs/cm)	ORP (mV)	T °C
Min	1.3	3.1	0.0	0.9	0.1	0.3	10.1	0.3	0.4	5.3	0.0	0.0	0.0
Max	2.9	9.1	0.2	3.2	0.3	5.2	158.1	0.6	2.7	8.4	392.7	195.0	30.2
Mean	1.9	6.3	0.1	1.6	0.1	0.9	44.5	0.4	1.0	6.9	132.0	148.4	27.8
Std Div	0.4	1.7	0.0	0.5	0.1	1.0	30.1	0.1	0.5	1.6	104.0	37.8	5.9
<i>Madawachchiya 50 cm (n = 25)</i>													
Min	1.3	5.3	0.0	0.7	0.0	0.2	12.5	0.3	0.3	5.7	21.3	108.0	29.0
Max	2.4	10.4	0.5	2.4	0.3	1.4	50.4	0.7	1.1	8.1	489.0	210.0	29.9
Mean	1.7	7.5	0.2	1.3	0.1	0.7	33.0	0.5	0.6	7.0	104.0	160.4	29.5
Std Div	0.3	1.5	0.1	0.4	0.1	0.3	10.5	0.1	0.2	0.6	103.7	21.8	0.2
<i>Padaviya Surface (n = 25)</i>													
Min	1.2	2.6	0.1	1.4	0.0	0.1	9.4	0.3	0.4	7.0	53.7	-100.0	22.0
Max	2.5	10.3	0.2	2.5	0.3	0.5	43.3	0.7	3.2	8.0	860.0	40.0	26.8
Mean	1.6	7.0	0.1	2.1	0.1	0.2	21.8	0.5	1.0	7.6	275.3	6.1	24.6
Std Div	0.3	1.9	0.0	0.3	0.0	0.1	8.1	0.1	0.5	0.2	159.0	38.3	1.3
<i>Padaviya 50 cm (n = 25)</i>													
Min	0.8	5.2	0.1	1.1	0.0	0.1	6.4	0.3	0.3	7.1	129.8	-42.0	25.0
Max	1.9	11.8	0.6	2.8	0.2	3.0	117.9	0.7	1.3	8.0	387.0	62.0	28.9
Mean	1.6	8.8	0.2	2.0	0.1	0.3	20.0	0.5	0.7	7.5	215.2	25.0	26.0
Std Div	0.3	1.8	0.1	0.4	0.0	0.6	20.5	0.1	0.3	0.3	73.6	27.7	1.4
UCC	0.50	5.04	0.10	4.20	0.15								

Cu (28.4), Ni (15), Cr (85.1), V (71.7), Zr (152.6), F (58.1) and electrical conductivity of 127.3. In Kabithigollawa, Pb (44), Zr (110.9), TS (174.2) and electrical conductivity (EC) of 315 show a high standard deviation. In Medawachchiya, Sr (127.5), TS (71.9), F (73.5), electrical conductivity (104.0) and ORP (37) obtained the highest standard deviation values. In Padaviya, Cr (71.7), Sr (69.4), Nb (72.3), Sc (75.8), F (95) and EC (159) obtained the high standard deviation values.

The Pearson correlation matrix (Supplementary Material 1) of the four study areas for the surface and 50 cm was generated separately. In the Horowpothana surface samples, elements that show high correlation of 0.8 and higher are Fe with V and Sc, Cu with Ni, Nb with Ti and Zr, V and Sc with Fe, and Zr with Th. In Kabithigollawa, elements show a high correlation for As with Pb and Th, Nb and Zr with Ti, Pb with Th and Cu with Ni. In Medawachchiya, Cu showed a high correlation with Sc, Fe and MnO, Ti with V and Nb, Nb with Zr, Sr with CaO. In Padaviya, V shows a higher correlation with Sc, Ti and Fe, Pb with TS and TS with Fe.

Elemental concentration variation in 50-cm samples

The minimum, maximum and the UCC values for each element in surface and 50-cm soils are given in Table 1. Out of the KBG samples, 24% shows a higher concentration than UCC (20 mg/kg) for Pb. For Zn, KBG 16%, HWP 16% and PDW 80% of samples exceeded the Zn concentration of UCC value of 71 mg/kg. The Cu content exceeded by 44% for KBG, 32% for MWC, 68% for HWP and 80% for PDW than UCC of 25 mg/kg. For Ni, UCC concentration of 20 mg/kg was exceeded in the KBG for 72%, MWC 60%, HWP 64% and PDW 80%. For the Sr concentration, KBG 40%, MWC 20% and PDW 20% exceeded UCC value of 350 mg/kg. The Y concentration of UCC of 22 mg/kg was exceeded in KBG by 12%, MWC 8%, HWP 80% and PDW 24% of the samples. The UCC concentration of 25 mg/kg of Nb was exceeded only in KBG for 8% and MWC for 24%. In KBG 16%, MWC 12% and HWP 42% showed higher concentration of Th than UCC value (11). The Sc concentration exceeded in KBG for 52%, MWC 60%, HWP 56% and PDW 90% than UCC value of 11 mg/kg.

The elements that show high standard deviation (Table 1) for the 50-cm samples are as follows: Horowpothana V (77.9), Zr (113.8) and TS (125.4). In Kabithigollawa, V (102.0), Y (83.0), Sc (51.9), TS (83.5) and electrical conductivity of 89.7 show high standard deviation values. Chromium (58.4), V (108.7), Sc (61.2) and F (73.1) showed the highest standard deviation values in Medawachchiya. In Padaviya, Cr (66), V (93), Zr (65.3), Sc (83.2), F (99.1), EC (73.6) and ORP (27.7) showed high standard deviation values.

In the 50-cm samples of Horowpothana, Nb with Zr and Ti, Th, Sc and Cu with Ti, V with Fe obtained higher correlations than 0.8 (Supplementary Material 1). In Kabithigollawa, V with Sc and Fe, Nb with Ti while Sc with TS obtained higher correlations. In Medawachchiya, V with Ti and Fe, Nb with Zr and Ti, Sc with Ca showed high correlations. In Padaviya, V with Sc, Ti, Fe and Th, Sc with Ti and Fe while Ti with Fe and Zn with P obtained higher correlations than 0.8.

Discussion

The mobility of metals is influenced by their connections with phyllosilicates, matter, variable charge minerals, and micro-organisms, pH, sorbent nature, root exudates and nutrients (Caporale & Violante, 2016; Violante et al., 2010). Some processes influence ion mobility of soil by such as surface complex formation, ionic exchange, precipitation, and adsorption processes (Fifi et al., 2013). These processes could increase the concentrations of harmful elements in the soils, which could be easily moved to the nearby water bodies or absorbed by the crops cultivated in the contaminated soils. The soil sampling has been done from household home gardens and agricultural lands that at least one or many patients live. Thus, due to (i) accumulation in soils and by (ii) consumed water or by (iii) crops absorbing the excess harmful elements, it could be consumed by humans, which may cause health effects.

In the dry zone areas where reddish brown earth soil is present, 'well', 'moderately', well or 'imperfectly drained' conditions prevail. Drainage conditions are poor or very poor only where low humic gley soils are present. The areas that have combinations of these two soils show different drainage conditions. High content of pyrite in reddish brown earth soils relates to the

oxidation, whereas the pH decreases towards the acidic conditions. When soil pH decreases, the availability and mobility of metal ions increase due to the change of chemical form in which these metal ions are present in soil solutions (Reddy et al., 1995).

Soil pH with Eh are the master variables of soils and greatly affect numerous soil chemical reaction processes (Sparks, 2003). Rainwater leaching away basic ions (calcium, magnesium, potassium and sodium), carbon dioxide from decomposing organic matter, root respiration dissolving in soil water to form a weak organic acid formation of strong organic and inorganic acids, such as nitric and sulphuric acid, from decaying organic matter and oxidation of ammonium and sulphur fertilizers are the most causative factors for change in soil pH fluctuating between acidity and basicity (Sposito, 2008). Generally dry zone soils are less acidic (Chandrajith et al., 2005). The pH of most of the samples varies within 6–9. The pH of some samples of HWP and PDW shows higher values in 50 cm than surface indicating basic condition in 50 cm than surface (Fig. 3 a, d) and correlates well with Chandrajith et al., 2005 findings. This may be due to the rainwater leaching through basic ions such as calcium and magnesium in subsurface soil, which indicates high CaO values in HWP 50 cm 0.68–2.32 and 50 cm PDW 1.07–2.79 Wt% (UCC 4.2 Wt%) in elemental analysis. pH of KBG and MWC shows relatively high fluctuation between surface and 50 cm and may indicate high mobility of ions (Fig. 3 b, c). In Horowpothana and Padaviya, the range of fluctuation is less, while in Kabithigollawa and Medawachchiya the range shows a high range of fluctuation between surface and 50-cm samples (Fig. 3).

The ORP is the measurement of the electron obtainability and electron potential of the soil system (DeLaune & Reddy, 2005). The primary source of electron in the soil is organic matter (Sparks, 2003). In addition, the reducing conditions of soils are most favourable for metal solubilisation. As Fig. 4 a, b, c, d shows, it is clearly seen that all samples of surface and 50 cm except few samples in Padaviya show positive ORP values. In Horowpothana, the ORP of 50-cm soil has high positive values than surface soils in all the locations. In Kabithigollawa, the ORP of most of the samples is high and found in the 50-cm samples, and in Medawachchiya most of the samples have positive values for ORP in the surface samples. In Padaviya, most of the 50-cm samples show high ORP. This

indicates that the 50-cm samples of almost all areas are oxidized than the surface. This may be an indication of anoxic condition of the surface soil, which is formed during the cultivated period and application of nitrate-containing fertilizer (Jayawardana et al., 2012). The highest ORP value was found in the KBG-25 (221.5 mV), which was from an agricultural land MWC-14 and was from a non-agricultural land, which are surface samples and consisted of high organic matter content of black soil, and thus, the organic matter may be the contributing factor.

The electrical conductivity of soils varies contingently on the extent of moisture held by soil particles, particle size and texture of the soil, where soils have a low conductivity, silts have a medium conductivity and clays have a high conductivity (Grisso et al., 2009). EC in most of the locations of HWP, KBG, PDW and MCW is higher in the surface than 50 cm (Fig. 5 a, b, c, d). This may be due to the high accumulation of soluble salts on the top surface than 50 cm mainly during the dry season, due to high evaporation and due to fertilizer application and soil preparation activities. Thus, it also indicates less leaching of ions to the bottom soil layers.

The high amount of CaO in 50-cm samples of HWP and PDW and high fluctuation of pH of KBG and MWC may influence leaching towards the groundwater sources and finally may accumulate in the human body, which in turn could become a causative factor for CKD for the people living in these four areas. The favourable relative reducing conditions obtained in the surface samples of all four villages comparative to 50-cm samples could favour the high amount of nitrate retention obtained by fertilizer application to the surface samples during the cultivated period. The reduced condition favours the retention of compounds such as nitrate and organic matter. This retention will increase the nitrate concentration in soils as well as waters in the area and, thus, also could be causative factors for the CKD due to the washout towards the drinking water bodies of the area (Wimalawansa, 2016), which will be consumed and finally cause adverse effects to the human body. The high EC values in surface samples also indicate the high amount of salt concentration close to the surface soils and may be due to high fertilizer application, heavy ploughing and high evaporation. These occurrences may cause the wash off of those salts to the nearby surface water resources and result in high concentrations of EC and

salts. The elements that are mainly heavy metals cause high salinity due to high EC, can finally accumulate in the human body and can be suggested to become a causative factor for CKD. The above discussion on variation of pH, EC and ORP in the surface and 50-cm soils is the evidence that these could help to identify the contributing factors that may be suggested to be causative for CKD due to soil conditions in the areas.

UCC normalization

There are various types of analytical methods in geochemistry to determine the compositional evolution, contamination and provenance signatures of soils. Based on the elemental concentrations, the UCC normalization (Taylor & McLennan, 1985) can be used to identify and differentiate the soils of each area and also to determine the differences in soil composition. Upon normalization, the resulted enrichments and depletions of elements are due to the geochemical processes of that area (Taylor & McLennan, 1985). When elements are enriched and if those elements are highly mobile, they can reach the nearby water bodies or can enter the humans through crops cultivated in the area. If these elements are toxic or harmful and are consumed in excess for a prolonged period, it could cause serious health effects to the population living in this area. The causes for CKD are still unknown, and since the CKD is widespread in these areas the enriched elements if environmentally hazardous could be causative factors for CKD. Therefore, to investigate the enrichments and depletions of elements in the soils, the UCC normalization for the soils was carried out.

Four areas show somewhat similar pattern in mean elemental variation for UCC normalization, but has few deviations. When consider the surface and 50 cm of each area, for each element, the values are almost similar except for a few elements. In Horowpothana for both surface and 50 cm, Ti, Fe, Cu, Ni, Cr, V, Zr, Th, Br and I show enrichment than UCC, while Ca, P, As, Pb, Zn, Sr, Nb and F are depleted (Fig. 6a). In Kabithigollawa, Ti, Fe, Ni, Cr, V, Zr, Br and I show enrichment than UCC in both surface and 50 cm (Fig. 6b), while Ca, P, As, Pb only 50 cm Zn, Y, Nb and F are depleted. In Medawachchiya, Ti, Fe, Mn, Cr, V, Zr, Sc, Br and I show enrichment than UCC for both surface and 50 cm, while Ca, P, As, Pb, Zn, Sr, Y and F are depleted (Fig. 6c). In Padaviya, Ti, Fe, Mn, Cu, Ni,

Cr, V, Zr, Sc, Br and I show enrichment than UCC in both surface and 50 cm samples, while Ca, P, As, Pb, Nb, Th and F are depleted (Fig. 6d). The patterns show somewhat similarities in Kabithigollawa and Medawachchiya except for a few deviations in enriched P_2O_5 , As and Pb in the surface samples of Kabithigollawa. Horowpothana and Padaviya are different from each other. However, Horowpothana and Padaviya are different from each other. The variation in number of CKD patients can be somewhat related to this patterns where Medawachchiya has the highest CKD patients. Then, Padaviya is followed by Horowpothana and the lowest number of CKD patients in Kabithigollawa, whereas at 2010, high incidence of CKD is mainly in the areas (where the cases are presently in approximation): Medawachchiya 2500, Girandurukotte 1500, Mahiyaganaya 800, Padaviya 1000, Medirigiriya 80, Dehiattakandiya 400, Nikawewa 400 and Kabithigollawa (Johnson et al., 2012).

In common, Ti, Fe, Cu, Ni, Cr, V and Zr are enriched, while Ca, P, As, Pb and Zn are depleted. The Sri Lankan rocks are mainly composed of mafic composition and are rich in Ti, Fe, Cu, Ni, Cr, V and Zr, which are also contributed by heavy minerals that are abundant in the Sri Lankan soils (Pohl and Emmerman, 1991; Young et al., 2013). The V of the soils is almost four times higher compared to UCC in both surface and 50 cm. Jayawardena et al. (2014) also have discussed that V may be a cause to CKD and are further evidenced in the present study. Thus, the heavy mineral-related elements Ti, Fe, Cu, Ni, Cr, V and Zr are abundant in all four areas that consist of large number of CKD patients, and these elements may be causative factors for the CKD problem that is caused due to the crustal composition where they are contributed from the heavy minerals such as zircon, monazite, apatite, titanite, garnet, rutile and tourmaline (Young et al., 2013) abundant in the dry zone soils. Chromium and V of 50 cm show a slightly higher enrichment than in the surface soils for all four areas (Fig. 6a, b, c, d) and are due to the mafic rocks that consist of high Cr and V in the Sri Lankan crust (Pohl and Emmerman, 1991), which forms weathered soil and undisturbed due to anthropogenic activities. In all four areas, fluoride is considerably depleted. Most of the researches argue that fluoride is the cause for CKD; however, the soils show low fluoride, and the cause is that fluoride is highly mobile with a high affinity and is mainly in the water of the area than in

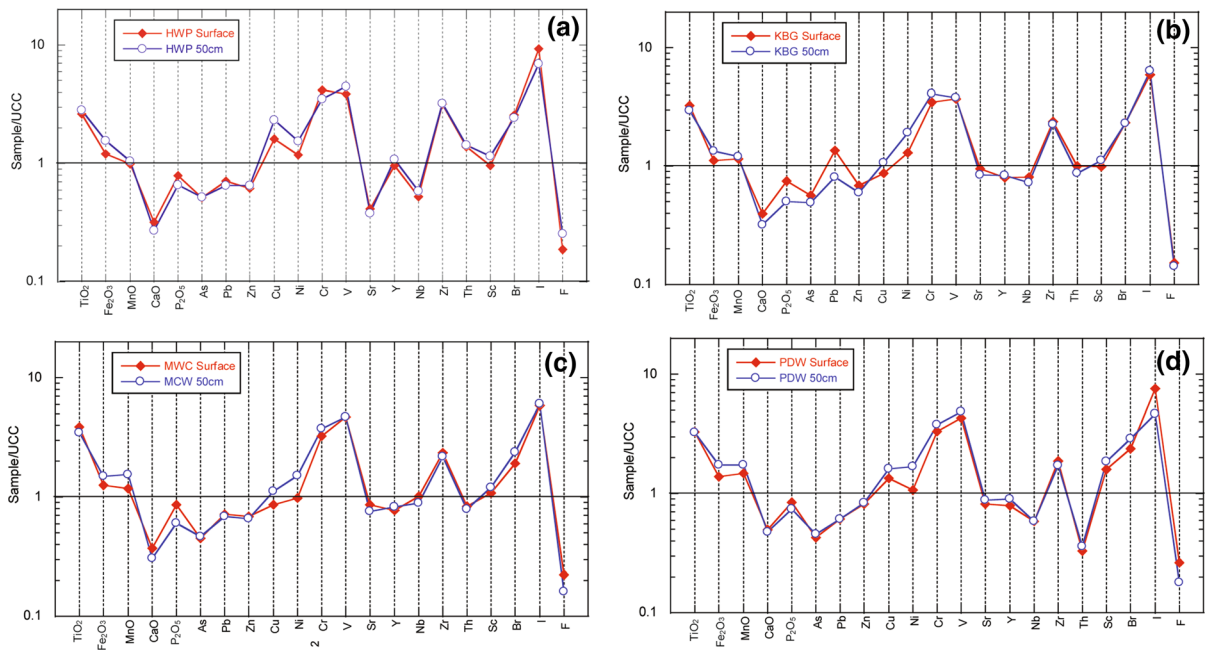


Fig. 6 Upper continental crust (UCC) normalization of the surface and 50 cm soils for the four areas

the soils (Ileperuma et al., 2009; Young et al., 2010). However, in order to find the exact relationship between the enriched elements Ti, Fe, Cu, Ni, Cr, V and Zr in soil and CKD, further studies including the elemental values in patients kidneys have to be done.

Provenance indicators

Probability of provenance, sorting or accumulation of heavy minerals (zircon, monazite, apatite) can be evaluated using Zr/Sc and Th/Sc ratios (McLennan et al., 1993). Th/Sc ratio can be used as the sensitive index to evaluate the bulk composition of the source (Taylor & McLennan, 1985), although Zr/Sc ratio assists as a proxy for classifying heavy mineral concentrations, because it is highly sensitive to accumulation of zircon. The plot positions and trends of bivariate Zr/Sc–Th/Sc give an indication of source composition and heavy mineral concentrations. The samples of all four areas plot from dacite to rhyolite in the order of Padaviya, Kabithigollawa, Medawachchiya and Horowpothana for both surface and 50-cm soil samples. Surface and 50-cm samples of Padaviya cluster closest to dacite, which indicates the same composition in all sampling points of the area. Almost all the surface and 50 cm samples of Kabithigollawa

cluster close to UCC, and few samples move towards and away from the rhyolite (Fig. 7a, b). In Horowpothana, all the surface and 50 cm samples scattered towards rhyolite and few samples move away from rhyolite indicating heavy mineral signatures. The surface and 50 cm samples of Medawachchiya vary between dacite and rhyolite, while few samples exceed the rhyolite and show enrichment in heavy minerals. Most of the samples of Medawachchiya, Kabithigollawa and Horowpothana show enrichment in heavy minerals. The plotting of the soils in different areas in the plot indicated that the soils of each area have different compositions. The clustering is high in the 50-cm samples in all four areas than the surface samples. The surface samples show a much scatter for all four areas indicating slight inputs from various sources.

The ratios of Cr/V–Y/Ni also provide estimates of preferential concentration of chromium over other ferromagnesian elements (Hiscott, 1984; McLennan et al., 1993). The enrichment of Cr with respect to other ferromagnesian elements measures the Cr/V ratio, whereas the Y/Ni ratio evaluates the relationship between the ferromagnesian trace elements. The surface samples of Padaviya, Medawachchiya, Kabithigollawa and Horowpothana spread over a

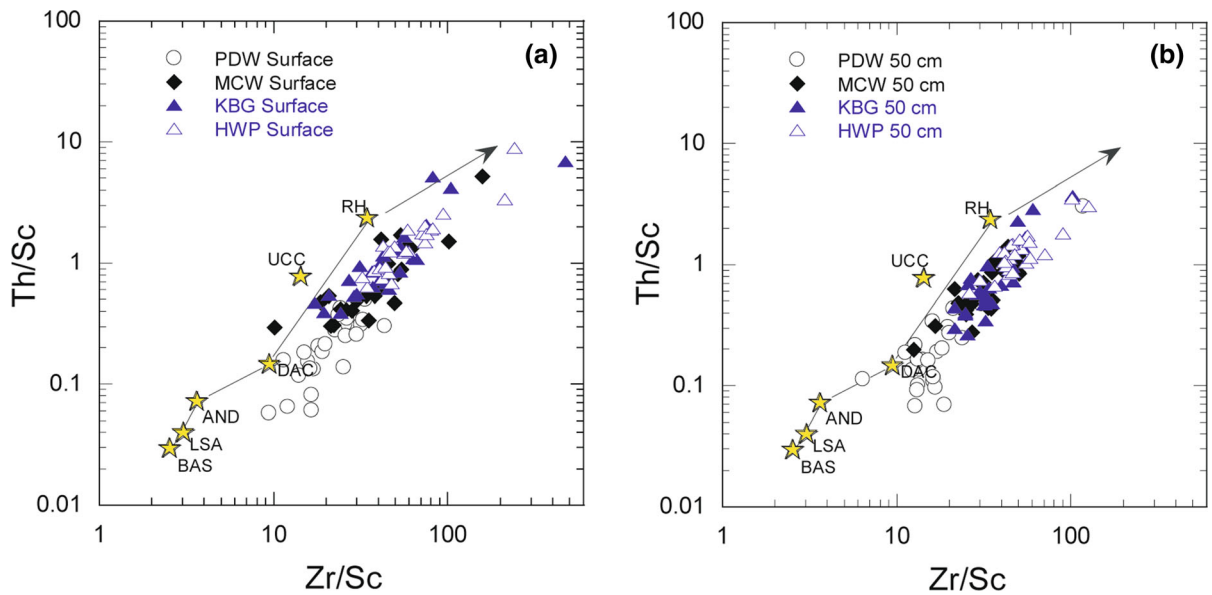


Fig. 7 Zr/Sc–Th/Sc ratio plots (McLennan et al., 1993) for (a) surface soils; (b) 50 cm soils. Stars BAS, AND, DAC, RHY: average basalt, andesite, dacite and rhyolite, as plotted by Roser and Korsch (1999)

larger area of Cr/V–Y/Ni graph with high scattering, while 50-cm samples spread over a narrow area with slight scattering (Fig. 8a & 8b), although four villages have same compositions except few samples in Kabithigollawa. Soils derived from ultrabasic sources have high Cr/V ratios (>> 1) coupled with low Y/Ni (< 1) (Hiscott, 1984) as shown in Fig. 8a and b; few samples of Kabithigollawa surface and 50 cm plot

close to ultrabasic composition, while all the other samples plot towards calc-alkaline (CA) composition.

The provenance of the soil of all four areas provides the evidence of the source of the soil parent material and their bulk composition. The high concentration of heavy mineral signatures in Horowpothana, Kabithigollawa and Medawachchiya could also relate to high CKD patients in these four areas. The close composition to ultrabasic in Kabithigollawa is a result of

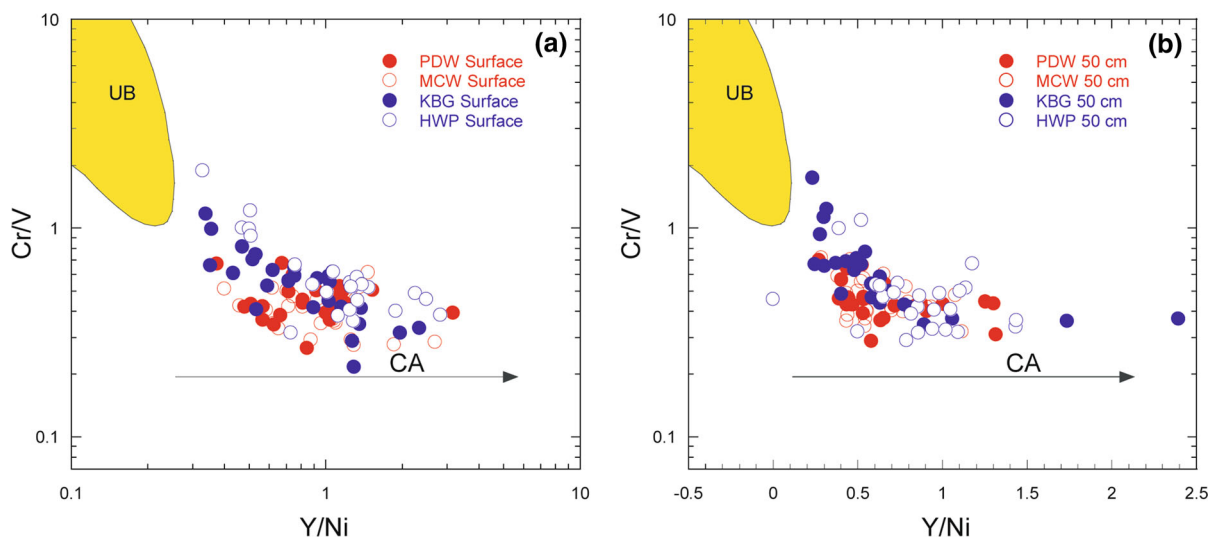


Fig. 8 Cr/V–Y/Ni plots (McLennan et al., 1993) for (a) surface soils; (b) 50 cm soils; CA—calc-alkaline

weathering of underlying rock with high amount of Cr concentration (Pohl and Emmerman 1991), while other three villages take a calc-alkaline trend. The common indication of heavy minerals in all four villages was a prominent feature. The heavy mineral-related elements Cu, Ni, Cr, V, Nb and Ti very clearly show very high mean values than UCC (Table 1) and high mean differences for almost all heavy mineral-related elements (those which are bold in Table 2) in all soils. Thus, it is clear that heavy mineral also could be a contributing factor for CKD by releasing heavy minerals to the water bodies consumed by the people in all these four villages.

Variation with iron

Heavy metals are well known to be related to the clay fraction (Robert et al., 2004). On the other hand, As, Pd and Zn are very sensitive to environmental changes, and they are easily absorbed on clay particles (Yuan et al., 2010). Iron is one of the main elements strongly associated with heavy metals, and it can exist in several phases (Gurzau et al., 2003). Thus, As, Pb and Zn have been cross-plotted with Fe_2O_3 to show the environmental changes and contamination (Figs. 9a, b, c & d, 10a, b, c & d, 11a, b, c & d). Almost all the locations of Padaviya, Horowpothana, Medawachchiya and Kabithigollawa show very low values compared to UCC values for As, Pb and Zn (5, 20 and 71, respectively, Taylor & McLennan, 1985). The Fe concentration is high in almost all the locations of surface and 50 cm samples. The Fe concentration of all the samples varies within 4–10 Wt%, while UCC is 4.5 Wt%.

Arsenic is found as a trace constituent in rocks and soils (Jayawardana et al., 2012). As concentration in rocks and soils is approximately 2 and 5 mg/kg. The weathering of rocks and microbial activities in soil mainly increases mobilization of As in soil (Garcia-Sanchez & Aluvarez-Ayuso, 2003). Arsenic concentration is very low in all the locations of surface and 50 cm samples and varies similarly within 1–3 mg/kg in all four villages (Fig. 9a, b, c & d). Arsenic concentration of surface and 50 cm samples of Horowpothana, Kabithigollawa and Medawachchiya shows high scattering, while all the samples of Padaviya cluster together. The Pb concentration varies within 8–24 mg/kg in all four areas (Fig. 10a, b, c & d). The Pb concentrations of almost all the locations of

Horowpothana, Medawachchiya and Padaviya surface and 50 cm samples cluster together, while Kabithigollawa shows high scattering. Pb can be considered as one of the least mobile heavy metals in the soil (Rosemary et al., 2014). This indicates the lower leaching ability of Pb throughout the vertical soil profile (Davies, 1984). As for Rosemary et al., 2014, contents of lead were significantly different in different land uses. In the current study, the mean Pb content in uncultivated soils was higher than cultivated soils. Jayewardana et al. (2012) observed 21, 28 and 32 mg/kg of Pb content in uncultivated soils of Madirigiriya, Talawa and Padaviya areas, respectively. Therefore, cultivated land soils did not show any enrichment of Pb in both surface and 50 cm in KBG, MWC, HWP and PDW, indicating non-agricultural sources, such as parent material and atmospheric deposition, may be caused for the enrichment of Pb (Rosemary et al., 2014).

The Zn concentration of all the areas varies within 20–110 mg/kg (Fig. 11a, b, c & d). In Horowpothana, Medawachchiya and Padaviya, the surface and 50-cm Zn concentrations plotted separately, and 50 cm plotted close towards high Fe concentrations, although in Kabithigollawa surface and 50 cm plotted as overlap with each location. MWC and both surface and 50 cm samples have a different chemical composition, while KBG and HWP surface and 50 cm samples have a similar chemical composition.

The high amount of iron oxide in all four villages is due to the weathering of underlying basement rock and comprises mainly reddish brown earth. The lower As concentration obtained in all samples except one in KBG—9 of these four areas indicates As could not be a causative factor for CKD, since Arsenic has not been accumulated in these four areas and it may be due to its anionic behaviour in nature (Jayawardana et al., 2014). Thus, the high values of Pb and Zn in some samples of these four villages may be due to the agricultural activities and weathering of parent material. However, since Pb and Zn are showing some high values in both agricultural and non-agricultural soils (Table 1, means and SD of all eight categories) of the area, it could be due to anthropogenic and natural activities and also could be one of the causative factors for CKD.

Table 2 Statistical summary of elemental concentration with mean and confidence intervals for surface and 50 cm soils of Horowpothana, Kabithigollawa, Madawachchiya and Padaviya

Mean		As	Pb	Zn	Cu	Ni	Cr	V	Sr	Y	Nb	Zr	Th
Surface													
Horowpothana (n = 25)		2.5	14.2	43.9	40.2	23.6	145.6	233.0	145.2	21.2	13.1	608.5	14.8
Kebithigollawa (n = 25)		2.7	27.1	49.0	21.8	26.0	121.2	222.2	333.3	17.6	20.2	454.5	10.8
Madawachchoya (n = 25)		2.2	14.4	48.9	21.6	19.7	114.4	283.5	301.7	17.0	25.3	449.8	8.9
Padaviya (n = 25)		2.0	12.2	57.9	33.7	21.5	116.3	259.9	286.3	17.4	14.6	355.6	3.5
50 cm													
Horowpothana (n = 25)		2.5	13.0	46.2	58.6	30.8	122.8	267.2	132.0	23.9	14.6	613.0	15.4
Kebithigollawa (n = 25)		2.4	16.2	42.6	26.8	38.3	143.9	227.6	294.7	18.4	18.1	428.5	9.3
Madawachchoya (n = 25)		2.2	13.7	46.9	27.9	30.4	131.6	283.6	264.8	18.2	22.2	417.4	8.5
Padaviya (n = 25)		2.2	12.2	60.1	40.0	33.8	132.2	290.1	309.1	20.1	14.6	330.7	3.9
95% Confidence Intervals (CI)													
Surface													
<i>Horowpothana</i>													
95% Confidence Interval for Mean	Lower Bound	2.3	12.3	37.4	28.5	17.5	110.5	203.5	127.3	19.9	11.3	545.5	12.2
	Upper Bound	2.7	16.2	50.3	52.0	29.8	180.7	262.6	163.1	22.4	14.9	671.5	17.4
<i>Kebithigollawa</i>													
95% Confidence Interval for Mean	Lower Bound	1.9	8.9	42.1	17.1	19.4	102.3	198.9	296.6	16.2	17.9	408.7	8.4
	Upper Bound	3.5	45.3	55.9	26.5	32.5	140.1	245.5	370.0	19.0	22.6	500.3	13.1
<i>Madawachchiya</i>													
95% Confidence Interval for Mean	Lower Bound	2.0	13.4	41.2	19.0	16.1	100.0	254.5	249.1	15.6	22.1	392.8	6.9
	Upper Bound	2.3	15.4	56.6	24.2	23.3	128.7	312.4	354.4	18.5	28.6	506.9	11.0
<i>Padaviya</i>													
95% Confidence Interval for Mean	Lower Bound	1.8	11.0	48.8	27.9	18.0	103.2	230.5	257.6	15.8	13.5	325.8	3.0
	Upper Bound	2.3	13.3	67.0	39.4	25.0	129.5	289.2	314.9	19.0	15.7	385.5	4.1
50 cm													
<i>Horowpothana</i>													
95% Confidence Interval for Mean	Lower Bound	2.3	12.2	41.1	42.3	26.1	103.2	235.0	112.4	21.4	12.7	566.0	13.6
	Upper Bound	2.7	13.8	51.2	74.9	35.4	142.5	299.3	151.7	26.5	16.4	660.0	17.2
<i>Kebithigollawa</i>													
95% Confidence Interval for Mean	Lower Bound	2.2	14.3	36.2	22.8	31.3	120.5	202.4	252.6	16.9	15.7	394.2	7.2
	Upper Bound	2.5	18.1	48.9	30.9	45.4	167.4	252.8	336.8	19.9	20.6	462.7	11.4
<i>Madawachchiya</i>													
95% Confidence Interval for Mean	Lower Bound	2.0	12.7	39.0	25.7	26.9	116.4	259.5	219.9	16.6	19.8	376.5	7.1
	Upper Bound	2.4	14.8	54.7	30.1	33.8	146.7	307.7	309.7	19.8	24.5	458.2	9.9
<i>Padaviya</i>													

Table 2 continued

Mean													
95% Confidence Interval for Mean	Lower Bound	2.0	11.2	55.4	34.8	29.2	118.0	262.4	270.0	18.4	13.4	303.4	3.2
	Upper Bound	2.4	13.3	64.8	45.3	38.3	146.5	317.7	348.3	21.7	15.8	357.9	4.7
Difference of CI for surface—50 cm (Upper Bound surface -Upper bound 50 cm and Lower bound surface—lower bound 50 cm)													
<i>Horowpothana</i>													
95% Confidence Interval for Mean	Lower Bound	0.0	0.1	-3.6	-13.8	-8.7	7.3	-31.6	14.9	-1.5	-1.5	-20.5	-1.4
	Upper Bound	0.0	2.3	-0.9	-22.9	-5.6	38.2	-36.7	11.5	-4.0	-1.4	11.5	0.2
<i>Kebithigollawa</i>													
95% Confidence Interval for Mean	Lower Bound	-0.3	-5.4	5.8	-5.8	-11.8	-18.2	-3.5	44.0	-0.8	2.1	14.5	1.2
	Upper Bound	1.0	27.2	7.0	-4.3	-12.9	-27.3	-7.3	33.2	-0.9	2.1	37.5	1.6
<i>Madawachchiya</i>													
95% Confidence Interval for Mean	Lower Bound	0.0	0.7	2.2	-6.7	-10.9	-16.4	-5.0	29.2	-1.0	2.2	16.2	-0.2
	Upper Bound	-0.1	0.6	1.9	-5.9	-10.5	-18.0	4.7	44.7	-1.3	4.1	48.7	1.1
<i>Padaviya</i>													
95% Confidence Interval for Mean	Lower Bound	-0.2	-0.1	-6.6	-6.9	-11.3	-14.8	-31.9	-12.4	-2.6	0.0	22.3	-0.3
	Upper Bound	-0.1	0.0	2.3	-5.8	-13.3	-17.0	-28.5	-33.4	-2.7	0.0	27.5	-0.6
Mean													
Surface	Sc	TS	F	Br	TiO ₂	Fe ₂ O ₃	MnO	CaO	P ₂ O ₅	pH	EC(μs/cm)	ORP(mV)	
Horowpothana (n = 25)	10.6	595.7	91.7	4.1	1.32	6.0	0.10	1.33	0.12	7.3	300.7	42.4	
Kebithigollawa (n = 25)	10.9	583.7	85.4	3.7	1.63	5.6	0.12	1.66	0.11	6.9	187.6	169.7	
Madawachchoya (n = 25)	11.9	516.3	89.8	3.1	1.94	6.3	0.12	1.55	0.13	7.0	132.0	148.4	
Padaviya (n = 25)	17.6	593.0	110.9	3.8	1.65	7.0	0.15	2.09	0.13	7.6	275.3	6.1	
<i>50 cm</i>													
Horowpothana (n = 25)	12.7	499.6	96.4	3.9	1.41	7.9	0.11	1.13	0.10	7.6	218.3	74.8	
Kebithigollawa (n = 25)	12.3	448.4	79.9	3.7	1.48	6.8	0.12	1.34	0.08	7.0	65.4	183.2	
Madawachchoya (n = 25)	13.3	460.7	61.3	3.7	1.75	7.5	0.15	1.28	0.09	7.0	104.0	160.4	
Padaviya (n = 25)	20.3	540.4	75.6	4.7	1.63	8.7	0.18	2.00	0.11	7.5	215.2	25.0	
<i>Mean Difference (M2-M1)</i>													
Horowpothana	2.05	-96.08	4.72	-0.19	0.09	1.81	0.01	-0.20	-0.02	0.26	-82.32	32.48	
Kebithigollawa	1.36	-135.36	-5.56	-0.05	-0.15	1.13	0.01	-0.32	-0.04	0.11	-122.23	13.50	
Madawachchoya	1.33	-55.64	-28.54	0.58	-0.19	1.19	0.04	-0.27	-0.04	0.01	-28.05	11.95	

Table 2 continued

Mean													
Surface		Sc	TS	F	Br	TiO ₂	Fe ₂ O ₃	MnO	CaO	P ₂ O ₅	pH	EC(μs/cm)	ORP(mV)
Padaviya		2.76	-52.60	-35.37	0.84	-0.02	1.71	0.03	-0.09	-0.01	-0.07	-60.18	18.84
<i>95% Confidence Intervals (CI)</i>													
Surface													
Horowpothana													
95% Confidence Interval for Mean	Lower Bound	9.0	493.9	65.1	2.7	1.11	5.3	0.08	1.18	0.10	7.2	248.1	34.7
	Upper Bound	12.2	697.6	118.3	5.6	1.53	6.8	0.12	1.48	0.14	7.4	353.2	50.0
Kebithigollawa													
95% Confidence Interval for Mean	Lower Bound	9.2	511.8	54.7	3.0	1.47	4.9	0.10	1.49	0.09	6.7	57.6	160.1
	Upper Bound	12.7	655.6	116.2	4.5	1.79	6.3	0.13	1.83	0.13	7.2	317.6	179.4
<i>Madawachchiya</i>													
95% Confidence Interval for Mean	Lower Bound	10.4	486.7	55.1	2.8	1.79	5.6	0.11	1.34	0.10	6.3	89.1	132.8
	Upper Bound	13.5	546.0	124.6	3.4	2.09	7.1	0.13	1.77	0.16	7.6	175.0	164.0
Padaviya													
95% Confidence Interval for Mean	Lower Bound	15.7	561.7	68.0	3.3	1.52	6.2	0.13	1.97	0.11	7.5	209.7	-9.7
	Upper Bound	19.4	624.2	153.9	4.4	1.77	7.8	0.17	2.21	0.15	7.6	340.9	21.9
50 cm													
<i>Horowpothana</i>													
95% Confidence Interval for Mean	Lower Bound	11.1	447.9	57.1	3.6	1.20	7.0	0.09	0.99	0.08	7.4	182.7	71.8
	Upper Bound	14.2	551.4	135.8	4.3	1.63	8.7	0.12	1.27	0.12	7.7	254.0	77.9
<i>Kebithigollawa</i>													
95% Confidence Interval for Mean	Lower Bound	10.4	427.0	45.4	3.4	1.33	6.1	0.10	1.20	0.06	6.8	28.4	175.5
	Upper Bound	14.3	469.8	114.4	4.0	1.63	7.5	0.14	1.48	0.09	7.3	102.4	190.9
<i>Madawachchiya</i>													
95% Confidence Interval for Mean	Lower Bound	12.0	435.4	31.0	3.1	1.64	6.9	0.12	1.13	0.07	6.7	61.2	151.4
	Upper Bound	14.5	486.0	91.6	4.2	1.86	8.1	0.19	1.44	0.11	7.2	146.8	169.4
<i>Padaviya</i>													
95% Confidence Interval for Mean	Lower Bound	18.1	506.1	35.6	3.8	1.51	8.0	0.13	1.84	0.10	7.4	184.8	13.5
	Upper Bound	22.5	574.6	115.5	5.5	1.74	9.4	0.22	2.16	0.13	7.6	245.5	36.4
Difference of CI for surface—50 cm (Upper Bound surface -Upper bound 50 cm and Lower bound surface—lower bound 50 cm)													
<i>Horowpothana</i>													
95% Confidence Interval for Mean	Lower Bound	-2.1	46.0	8.1	-0.9	-0.1	-1.7	0.0	0.2	0.0	-0.2	65.4	-37.1
	Upper Bound	-2.0	146.1	-17.5	1.3	-0.1	-1.9	0.0	0.2	0.0	-0.3	99.2	-27.9

Table 2 continued

Mean		Sc	TS	F	Br	TiO ₂	Fe ₂ O ₃	MnO	CaO	P ₂ O ₅	pH	EC(μs/cm)	ORP(mV)
<i>Kebithigollawa</i>													
95% Confidence Interval for Mean	Lower Bound	-1.1	84.9	9.3	-0.3	0.1	-1.1	0.0	0.3	0.0	-0.1	29.2	-15.5
	Upper Bound	-1.6	185.9	1.8	0.5	0.2	-1.2	0.0	0.4	0.0	-0.1	215.2	-11.5
<i>Madawachchiya</i>													
95% Confidence Interval for Mean	Lower Bound	-1.7	51.3	24.1	-0.4	0.2	-1.3	0.0	0.2	0.0	-0.4	27.9	-18.6
	Upper Bound	-1.0	60.0	33.0	-0.8	0.2	-1.1	-0.1	0.3	0.0	0.4	28.2	-5.3
<i>Padaviya</i>													
95% Confidence Interval for Mean	Lower Bound	-2.4	55.6	32.4	-0.5	0.0	-1.8	0.0	0.1	0.0	0.1	24.9	-23.2
	Upper Bound	-3.1	49.6	38.4	-1.2	0.0	-1.7	-0.1	0.1	0.0	0.0	95.4	-14.5

Enrichment factor (EF)

The enrichment factor (EF) is a useful tool to evaluate the potential environmental contamination, as it can be used to differentiate between lithogenic and naturally occurring metal sources and to assess the degree of anthropogenic influence. Heavy metal contents are strongly correlated with Fe₂O₃, suggesting that Fe oxides play a significant role in controlling abundances. The EF for Fe-normalized data is defined by Zhang & Liu, 2002 as:

$$EF_{\text{metal}} = (M/Fe)_{\text{sample}} / (M/Fe)_{\text{UCC}}$$

where M and Fe are the concentrations of the metal and Fe in the sample, respectively, and M and Fe are the concentrations of the metal and Fe in UCC, used as an index of upper continental crust composition. Metal EF values of 0.5–1.5 suggest that the trace metals concerned may be derived from entirely from crustal materials or natural weathering processes (Zhang & Liu, 2002). The values greater than 1.5 suggest that a significant portion of the trace metal has been derived from non-natural (anthropogenic) sources (Zhang & Liu, 2002). EF values of < 1 indicate background concentrations; values of 1–2 depletion to minimal enrichment suggestive of no or minimal pollution; 2–5

moderate enrichment; 5–20 significant enrichment; 20–40 very high enrichment; and > 40 extremely high enrichments (Sutherland, 2000).

Enrichment factor of As, Pb, Zn, Cu and Ni varies close to 0.5 and 1.5 in almost all the locations of both surface and 50 cm (Supplementary material 2). These trace metal concerned may be derived entirely from crustal materials or natural weathering processes (Zhang & Liu, 2002). The EF of Cr lies within 2–5 in all the locations for both surface and 50 cm samples, which indicates high enrichment in soil (Supplementary material 2). These enrichments of Cr may be related to the local lithology, since Sri Lankan basement contains high Cr (Pohl and Emmerman, 1991; Cr values 5–688 mg/kg in Young et al., 2013), and there are no industrial point sources for contamination within these areas. Table 1 shows that Cr has a much higher value than UCC (116.2–145.9 mean while UCC is 35), and also the 95% confidence interval for mean and mean differences in Table 2 shows that Cr is very high in all eight categories. Therefore, this enrichment of Cr in almost all the locations and Pb, Zn, Cu and Ni in few locations among the people living in these four villages could be causative factors for CKD.

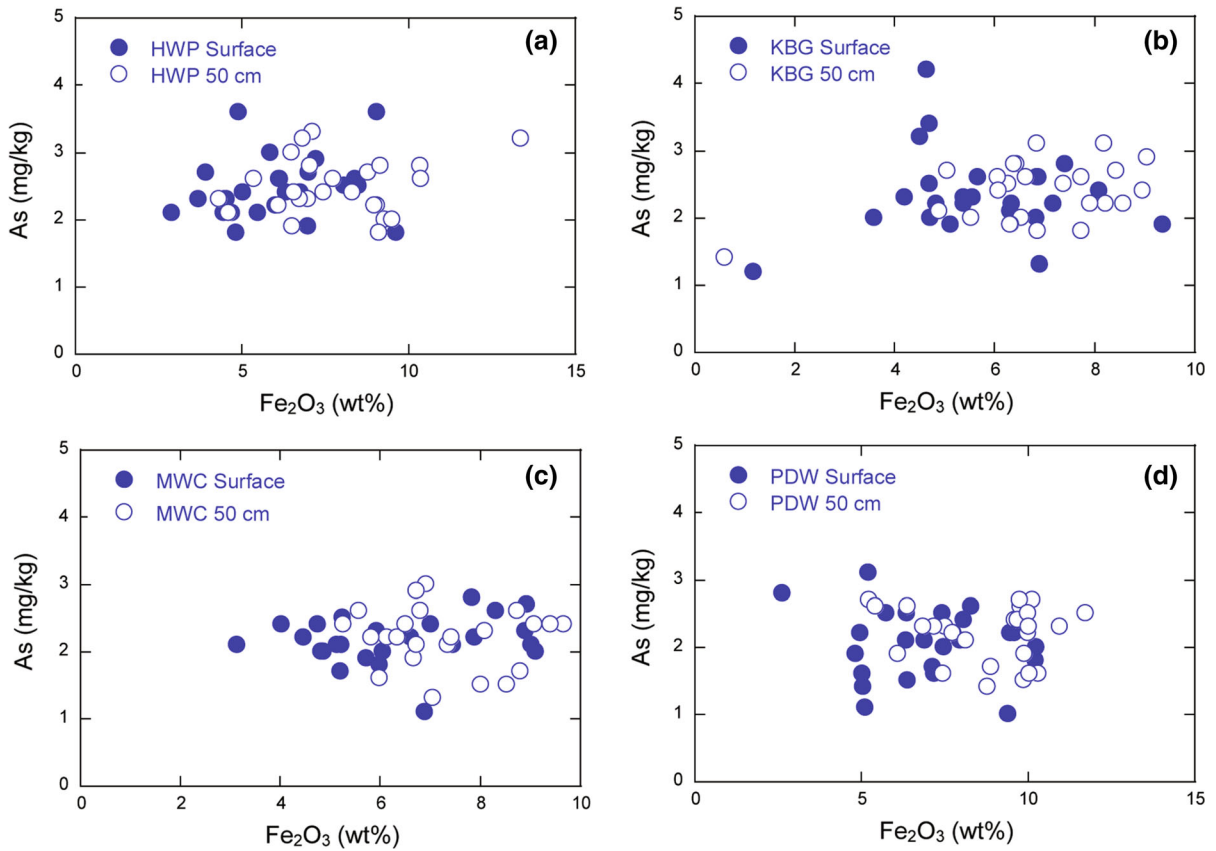


Fig. 9 As–Fe₂O₃ plots showing difference of composition showing provenance and environmental status for surface and 50 cm soils for the four areas

Surface and 50-cm elemental variation

In soil generally, soil properties, soil conditions and elemental concentrations vary both horizontally and vertically (Murray et al., 2004). Therefore, information about the mobility of the elements in the vertical soil profile is essential for predicting the environmental impact of elements (Kubova et al., 2008). Physio-chemical properties of the soil are one of the main causative factors for metal transportation in soil. Metals and metalloids may be found as one or more of the following forms in soil, such as dissolved (in soil solution), exchangeable (in organic and inorganic components), structural components of the lattices of soil minerals, insoluble precipitates with other soil components (Aydinalp & Marinova, 2003). The soil’s ability to retain and immobilize heavy metals and metalloids is determined by the cation exchange

capacity (CEC), pH, organic matter content, quantity and type of clay minerals, the content of the oxides of iron (Fe), aluminium (Al), and manganese (Mn), and the redox potential (Aydinalp & Marinova, 2003).

Thus, the elemental variation between the surface and 50 cm soil layers has been used to understand the mobility of ions. The ion mobility is very important to understand the pathway of the elements and its existence. The pathway of elements and the existence will reveal whether the element can enter the human through consumption causing health effects.

The data in Table 1 show the elemental variation (minimum, maximum values) of the surface and the 50 cm soil samples. In all four villages where Fe₂O₃, F⁻ shows extremely high variation within surface and 50 cm soils, while As, Zn, Ni, Sc, CaO and P₂O₅ (Table 1) show somewhat high variation between the surface and 50 cm.

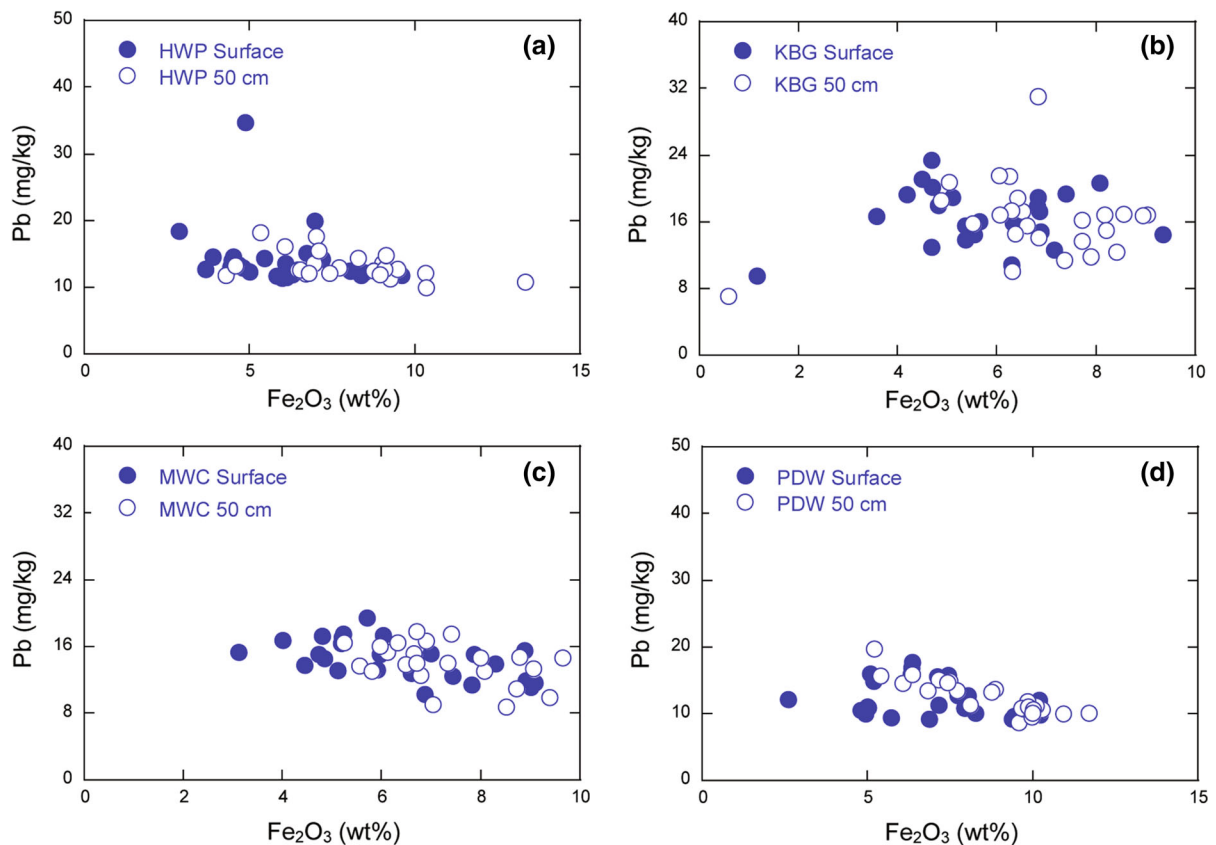


Fig. 10 Pb–Fe₂O₃ plots showing difference of composition showing provenance and environmental status for surface and 50 cm soils for the four areas

This variation is due to high mobility of these elements through the soil profile. The low rainfall received during the sampling period in this area and the rain water is slightly acidic (Ileperuma, 2000). Hence, the acid-soluble fraction of these elements may significantly dissolve and gradually become mobile between surface and 50 cm depth and enable leaching to groundwater. Dry zone soils are dominated by kaolinite with minor illites (Chandragith et al. 2004). The mineral composition of clay particle consists mainly of kaolinite, which has very strong sorption capacity. The chemical content of certain hydrous silicates and cations such as Mg²⁺, Al³⁺, Fe³⁺, Ni²⁺, Mn²⁺, and Fe²⁺ impacts on the chemical adsorption of F⁻ (Omeuti & Jones, 1977). Therefore, high mobility of F⁻ in all four villages may be controlled by the high content of Fe₂O₃ and high kaolinite clay content in surface and 50 cm soil samples. Niobium (Nb), Zr and Th show slight variation between surface and 50 cm in

all four villages (Table 2). Strontium, V, TiO₂, Pb and MnO show no variation in all four villages (Table 2).

The elements Nb, Zr, Th, Sr, V, TiO₂, Pb and MnO can be derived from the weathering products of opaque minerals, mainly found in the alkaline rock of the basement and application of agrochemicals including fertilizers such as apatite and also consecutive farming throughout the year. The lower mobility of Sr, V, TiO₂, Pb and MnO facilitated may be by their association with clay and cationic nature rather than other prevailing conditions. The mobility of fluoride tends to be a function of system pH and fluoride levels, soil type, with retention being favoured in acidic sediments containing clays and poorly ordered hydrous oxides of aluminium (Hong et al., 2016). According to the current study, due to the high mobility seen in F⁻ and Fe₂O₃ ions these could easily be mobilized to the groundwater of the area and thereby be related to the highest recorded CKD patients in these areas.

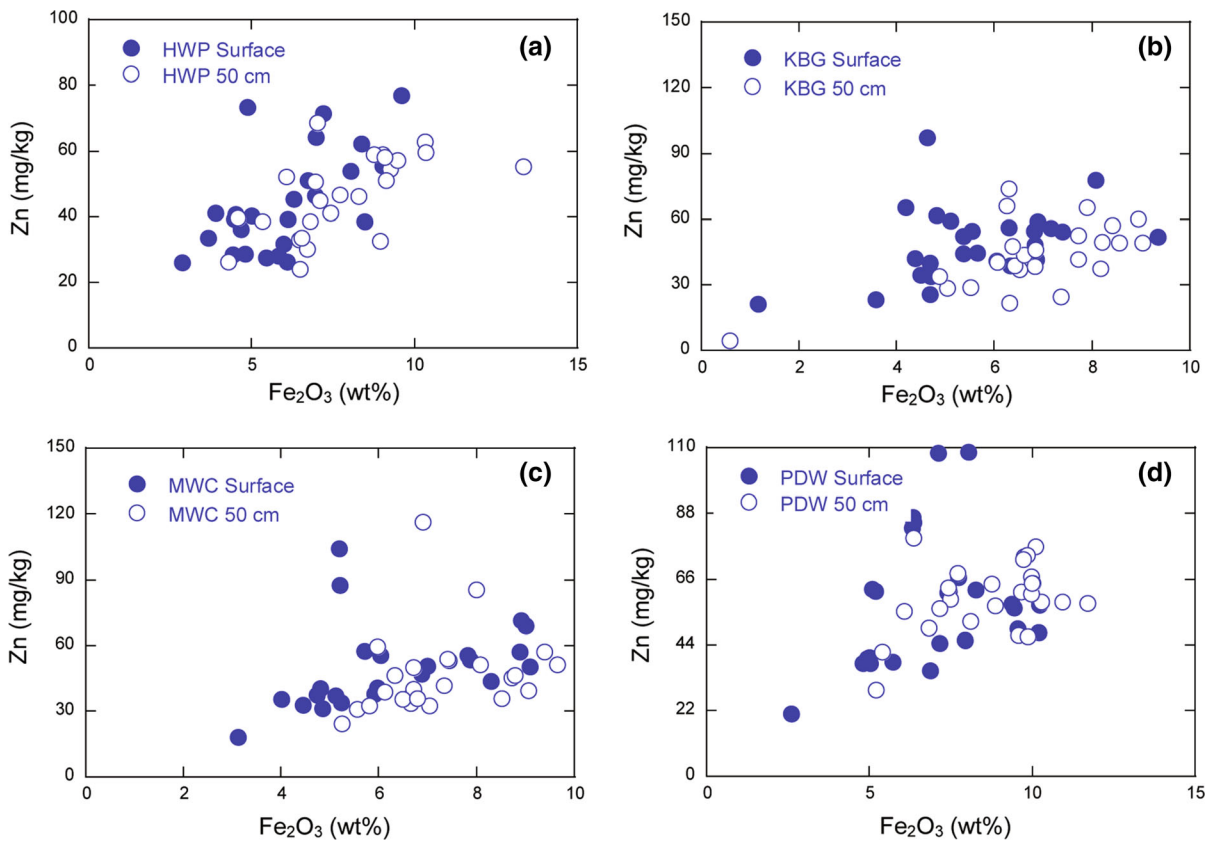


Fig. 11 Zn–Fe₂O₃ plots showing difference of composition showing provenance and environmental status for surface and 50 cm soils for the four areas

The soils of these areas are severely bound to dry conditions falling within the dry zone of the country since the area is bound to a prolonged arid condition of almost eight to nine months. The oxidic conditions of the soil in these four areas are due to the high amount of mixture of iron oxides with variable amounts of kaolinite and highly insoluble accessory minerals such as quartz sand (Foth, 1991). Most of the elements resulted from weathering of alkaline rock of the basement, and application of agrochemicals including fertilizers is present as a cations. These mainly absorb or bind with clay minerals or with the Fe₂O₃ in top surface soil and do not leach into the subsurface. The slightly acidic and heavy rains that are received in these areas during a short period enable the surface-bound elements to leaching through the soil as finer particles with an increased mobility.

When considering the surface and 50 cm separately, the mean values for each element for all the four villages are somewhat similar except a few cases

(Table 2). However, when consider the mean difference, it shows that there is a difference between the mean values between surface and 50 cm for each element (Table 2).

When calculate the confidence interval (CI) for 95% confidence, it gives the lower and upper bounds within which 95% of the samples' elemental concentrations are included. Statistically, it shows that there is a large difference between the ranges obtained in the CI (95% confidence) for both 'surface' and '50 cm below' samples. The elements with large difference are Sr, Zr, TS and the parameters EC and ORP for all the four villages (Table 2). This indicates that the elemental concentrations are within a large range for Sr, Zr, TS, EC and ORP. Strontium and Zr are mainly associated with heavy minerals. The negative values obtained for ORP in the CI difference indicate that the 50 cm has a higher bound than the surface in all four villages. Thus, as shown earlier, the 50 cm samples of almost all areas are oxidized than the surface.

Except Horowpothana, all other villages show a large difference for Ni and Cr (Table 2). Fluoride shows a very large difference for Medawachchiya and Padaviya and for the upper bound of Horowpothana and considerable difference for the lower bound of Kabithigollawa (Table 2). Vanadium shows a large difference for Horowpothana and Padaviya (Table 2). Copper shows a large difference for Horowpothana, while it shows somewhat difference for all other three villages indicating different values of elemental concentrations in different villages. However, except a few cases the upper bound and the lower bound values for 95% confidence are almost similar (As, Pb, Zn, Y, Nb, Th, Sc, Br, Ti, Fe, Mn, Ca, P and pH) for almost all the four villages indicating similar values of elemental concentrations in different villages. However, with the geological features and conditions of the independent locations elemental concentrations show differences and it is not reflected in such an analysis.

Soil pedagogical activities

Since a high proportion of quartz gravel is present in these areas, the depth to the gravel layer is variable (Panabokke, 1996) causing changes in the mobility of ions through each soil layer. Since the area is bound to heavy rains for a period of three to four months, the highest moisture in the soil is retained within this period where the soil will undergo specially, chemical weathering and also heavy runoff removing most of the ions from the top soil layers to the bottom soil layers. In the agricultural lands, the ploughing causes the mixing and changing the top soil and the bottom soil. This mixing causes the elements to shift from one layer to another in an uneven manner throughout the soil profile in each area. Thus, the areas that have heavy agricultural activity and that use high amounts of agrochemicals are subjective to this mixing process where the geochemical processes within the soil layers are controlled by the continued agricultural activities. This intern gives vast differences in the elemental variation in the top and 50 cm soil layers even in adjacent soil profiles. Further, resulting from the soil formation process, 60–80% reddish brown earth soil with moderate gravel associated with the 15–35% low humic gley soil is seen in this region (De Alwis & Panabokke, 1972). Thus, the absorption, adsorption and coagulation of heavy metals into the humic soils can take place easily. The area consists of reddish

brown soils and usually is composed of high contents of Fe in this area contributing mainly in oxic and anoxic properties of the soil. A study on salinity of the soils carried out by Perera, 2016 reveals that the soil salinity has increased with the increase in cropping duration in agro-well lands and the agro-well development has been accelerated in the dry zone areas. It has been predicted that after the next 25 years EC values can be increased up to ‘medium salinity level’ (up to 0.4 dS/m) in these dry zone areas. Thus, the intense agricultural activities as well as the natural activities with harsh climatic conditions have contributed to release and increased the mobility of many harmful elements, especially such as F^- , Cr, Sr, V, Ti, Pb and Zn within soil layers. Due to the high mobility of these harmful elements, they can easily move to nearby water bodies and enter the food chain causing accumulation in human body causing health concerns. The surface and 5 cm soils show higher than UCC values for these elements (Table 1). Thus, accumulation can occur for harmful elements in the human body for a prolonged period. In turn, these elements that are high in soil could be causative factors for CKD.

Conclusions

The soil of all four villages mainly has basic pH conditions. The iron mobility between surface and 50 cm is much higher in Horowpothana and Padaviya than Kabithigollawa and Medawachchiya indicating high activity of water and soil-related geochemical processes in Horowpothana and Padaviya areas, when in excess Ti, Fe, Cu, Ni, Cr, V and Zr elements are harmful to human health, and also since they are associated with heavy minerals, they can easily accumulate in the body. Titanium, Fe, Cu, Ni, Cr, V and Zr, which are heavy mineral signatures, are found in high concentrations in Horowpothana, Kabithigollawa and Medawachchiya. These areas also report high number of CKD patients, and the number of patients corresponds well with the elemental concentrations as mentioned in the text. Since the reasons for CKD are still unknown, there could be a relationship with the high mean concentrations (mg/kg) of Ti (1.3–1.9), Fe (5.6–8.8), Cu (21.8–58.6), Ni (19.7–58.6), Cr (114.4–143.9), V (222.2–291.9) and Zr (328.9–613.0) and high number of CKD patients in these four areas. Thus, these elements, specially the

high abundance of vanadium mg/kg (mean of 222.2–291.9; UCC 60), could be contributing factors to the CKD problem, which are caused due to the natural crustal composition, where they are contributed from the heavy minerals.

Kabithigollawa surface and 50-cm soil and surface samples take a calc-alkaline trend. The 50-cm soils of all four areas are in the oxidized condition, while surface soil is in the anoxic condition. The high EC values in surface samples also indicate the high amount of salt concentration close to the surface soils and may be due to fertilizer application and high evaporation, which may cause the wash off of these salts to the surface water resources and finally accumulate in human body and can become a contributing factor for CKD.

The present study reveals that arsenic could not be a causative factor for CKD, while the high values of Pb and Zn in some samples due to anthropogenic activities and specially elements related to heavy mineral that undergo natural weathering also could relate to CKD. EF of As, Pb, Zn, Cu and Ni are very low, which indicates origin is entirely from crustal materials or natural weathering processes. The EF of Cr is related to the local lithology, since the Sri Lankan basement contains high Cr and there are no industrial point sources for contamination within these areas. Therefore, this enrichment of Cr in almost all the locations and Pb, Zn, Cu and Ni in few locations which are harmful when in abundance in these four villages could be contributing factors for CKD.

The mineral formation is related to soil-forming processes or pedagogical activities of the North Central area, which undergoes a substantial drought for almost nine months and undergoes heavy rains for the rest of the period annually. Therefore, the mobility of irons with the different soil chemical properties could vary in the four areas studied. This explains the high mobility of ions in Horowpothana and Padaviya compared to the other two areas. High fluctuation between surface and 50 cm may indicate high mobility of ions. According to the current study, F^- and Fe_2O_3 ion could easily be mobilized into the groundwater of the area and thereby be related to the highest recorded CKD patients in these areas. Thus, the elements that could relate to be causative factors for CKD are Fe_2O_3 , Pb, Zn, Cr, F^- , Ti, Cu, Ni, V and Zr. This further implies that the causative factors for CKD are multi-factorial and have to be studied in detail with

patients, medical officers and the anthropogenic and natural geochemistry of the area.

Acknowledgements The authors acknowledge Mr Erabadupitiya, from the Agriculture Department, Anuradhapura for the support given for transport facilities, and also we thank the students of Shimane University, Japan, for the support given in soil analysis.

References

- Aydinalp, C., & Marinova, S. (2003). Distribution and forms of heavy metals in some agricultural soils. *Polish Journal of Environmental Studies*, 12, 629–633
- Caporale, A. G., & Violante, A. (2016). Chemical processes affecting the mobility of heavy metals and metalloids in soil environments. *Current Pollution Reports*, 2(1), 15–27
- Chandrajith, R., Dissanayake, C. B., & Tobschall, H. J. (2005). Geochemistry of trace element in paddy (rice) soils of Sri Lanka: Implications for Iodine deficiency disorders (IDD). *Environmental Geochemistry and Health*, 27, 55–64
- Chandrajith, R., Nanayakkara, S., Itai, K., Aturaliya, T. N., Dissanayake, C. B., Abeysekera, T., et al. (2010). Chronic kidney disease of uncertain etiology (CKDu) in Sri Lanka: geographic distribution and environmental implications. *Environmental Geochemistry and Health*, 33(3), 267–278
- Chandrajith, R., Dissanayake, C. B., Ariyaratna, T., Herath, H. M., & Padmasiri, J. P. (2011a). Dose-dependent Na and Ca fluoride-rich drinking water—another major cause of chronic renal failure in tropical arid regions. *Science of the Total Environment*, 409, 671–675
- Chandrajith, R., Nanayakkara, S., Itai, K., Aturaliya, T. N. C., Dissanayake, C. B., Abeysekera, T., et al. (2011b). Chronic kidney diseases of uncertain etiology (CKDu) in Sri Lanka: geographic distribution and environmental implications. *Environmental Geochemistry and Health*, 33(3), 267–278.
- Cooray, P. G. (1984). *The geology of Sri Lanka (Ceylon)*. (p. 340). National museums of Sri Lanka publication.
- Davies, J. A. (1984). Complexation of trace metals by adsorbed natural organic matter. *Geochimica Et Cosmochimica Acta*, 48, 679–691
- De Alwis, K.A. and Panabokke, C.R. (1972). *Handbook of the soils of Sri Lanka (Ceylon)*, Sri Lanka.
- DeLaune, R. D., & Reddy, K. R. (2005). *Encyclopedia of soils in the environment*. (pp. 366–371). Elsevier, Academic Press.
- Fifi, U., Winiarski, T., & Emmanuel, E. (2013). Assessing the mobility of lead, copper and cadmium in a calcareous soil of Port-au-Prince, Haiti. *International Journal of Research and Public Health*, 10(11), 5830–5843
- Garcia-Sanchez, A., & Aluarez-Ayuso, E. (2003). Arsenic in soils and waters and its relation to geology and mining activities (Salamanca Province, Spain). *Journal of Geochemical Exploration*, 80(1), 69–79
- Garzanti, E., & Andò, S. (2019). Heavy minerals for junior woodchucks. *Minerals*, 9, 148. <https://doi.org/10.3390/min9030148,2-25>

- Grisso, R.B., Wysor, M.A.W.G., Holshouser, D., Thomason, W. (2009) Precision farming tools: Soil electrical conductivity, produced by communications and marketing. College of Agriculture and Life Sciences, Virginia Polytechnic Institute and State University, publication 442–508.
- Gunatilake, S. K., Samaratunga, S. S., & Rubasinghe, R. T. (2014). Chronic Kidney Disease (CKD) in Sri Lanka - current research evidence justification: A review. *Sabaragamuwa University Journal*, 13(2), 31–58.
- Gurzau, S. E., Neagu, C., & Gurzau, A. E. (2003). Essential metals—case study on iron. *Ecotoxicology and Environmental Safety*, 56, 190–220
- Hiscott, R. N. (1984). Ophiolitic source rocks for Tectonic-age flysch: Trace element evidence. *Geological Society of America Bulletin*, 95(1), 1261–1267
- Hong, B. D., Joo, R. N., Lee, K. S., Lee, D. S., Rhie, J. H., Min, S. W., et al. (2016). Fluoride in soil and plant. *Korean Journal of Agricultural Science*, 43, 522–536
- Illeperuma, O. A. (2000). Environmental pollution in Sri Lanka: A Review. *Journal of National Science Foundation Sri Lanka*, 28(4), 301–325
- Illeperuma, O. A., Dharmagunawardhane, H. A., & Herath, K. P. R. P. (2009). Dissolution of aluminium from sub-standard utensils under high fluoride stress: A possible risk factor for chronic renal failure in the North-Central Province. *Journal of National Science Foundation Sri Lanka*, 37, 219–222
- Jayathilaka, N., Maheepala, P., Mendis, S., Mehta, F.R., Disanayake, L.J., & Janakan, N. (2013). WHO-CKDu-final report. WHO Sri Lanka CKDu report: Chronic kidney disease of unknown aetiology (CKDu): A new threat to health. World Health Organization. <http://dh-web.org/place.names/posts/index.html#ckdu>.
- Jayasekera, J.M.K.B., Dissnayake, D.M., Ratnayake P., Wikramasinghe, W., Radella, Y.A., & Palugaswewa, W. B. (2012). The effects from concentrated water on reservoirs of high prevalence areas on CKD of unknown origin in Sri Lanka on mice (Abstract.). Sri Lanka Medical Association annual scientific sessions.
- Jayasumana, C., Gunatilake, S., & Senanayake, P. (2014). Glyphosate, hard water and nephrotoxic metals: Are they the culprits behind the epidemic of chronic kidney disease of unknown etiology in Sri Lanka. *International Journal of Environmental Research and Public Health*, 11, 2125–2147
- Jayawardana, D. T., Pitawala, H. M. T. G. A., & Ishiga, H. (2012). Geochemical assessment of arsenic and selected trace elements in agricultural and non-agricultural soils of Sri Lanka. *Tropical Agriculturist*, 160, 1–19
- Jayawardana, D. T., Pitawala, H. M. T. G. A., & Ishiga, H. (2014). Assessment of soil geochemistry around some selected agricultural sites of Sri Lanka. *Environmental Earth Science*, 71, 4097–4106
- Johnson, S., Misra, S. S., Sahu, R., & Saxena, P. (2012). Environmental contamination and its association with chronic kidney disease of unknown etiology in North Central Region of Sri Lanka, Centre for Science and Environment, Lodhi Road, New Delhi.
- Kimura, J., & Yamada, Y. (1996). Evaluation of major and trace element XRF analyses using a flux to sample ratio of two to one glass beads. *Journal of Mineralogy, Petrology and Economic Geology*, 91, 62–72
- Kubova, J., Matus, P., Bujdos, M., Hagarova, I., & Medved, J. (2008). Utilization of optimized BCR three-step sequential and dilute HCl single extraction procedures for soil–plant metal transfer predictions in contaminated lands. *Talanta*, 75(4), 1110–1122
- McLennan, S. M., Hemmings, S., McDaniel, D. K., & Hanson, G. N. (1993). Geochemical approaches to sedimentation, provenance and tectonics. *Geological Society of America*, 284, 21–40
- Moorman, F.R., & Panabokke, C.R. (1961) Soils of Ceylon, A new approach to the identification and classification of the most important soil groups of Ceylon, Government press, Ceylon, pp 69.
- Murray, K. S., Rogers, D. T., & Kaufman, M. M. (2004). Heavy metals in an urban watershed in southeastern Michigan. *Journal of Environmental Quality*, 33, 163–172
- Omeuti, J. A. I., & Jones, R. L. (1977). Fluoride adsorption by Illinois soils. *Journal of Soil Science*, 28, 564–572
- Ogasawara, M. (1987). Trace element analysis of rock samples by X-ray fluorescence spectrometry, using Rh anode tube. *Bulletin of the Geological Survey of Japan*, 38(2), 57–68
- Panabokke, C.R. (1996). Soils and Agro-ecological environments of Sri Lanka. Sri Lanka. Sri Lanka. *Natural resources energy and research authority*.
- Perera, W. P. R. T., Dayananda, M. D. N. R., & Liyanage, J. A. (2020). Exploring the root cause for chronic kidney disease of unknown etiology (CKDu) via analysis of metal ion and counterion contaminants in drinking water: A study in Sri Lanka. *Journal of Chemistry*. <https://doi.org/10.1155/2020/8670974>
- Perera, M. P. (2016). Development of agro-well lands and Its impact on soil salinity in the North Central Dry Zone of Sri Lanka. *International Journal of Science and Research*. <https://doi.org/10.21275/v5i7.ART2016217>
- Pohl, J.R., & Emmermann, R. (1991). Chemical composition of the Sri Lankan Precambrian Basement. In *The crystalline crust of Sri Lanka, part 1, summary of research of the German-Sri Lankan consortium*. Geological Survey Department of Sri Lanka, Paper 7, 94–124.
- Reddy, K.J., Wang, L., Gloss, S.P. (1995). Solubility and mobility of copper, zinc and lead in acidic environments. In: Date R.A., Grundon N.J., Rayment G.E., Probert M.E. (eds) *Plant-Soil Interactions at Low pH: Principles and Management. Developments in Plant and Soil Sciences, Proceedings of the Third International Symposium on Plant-Soil Interactions at Low pH, Brisbane, Queensland, Australia*, 12–16 September 1993.
- Robert, S., Blanc, G., Schafer, J., Lavaux, G., & Abril, G. (2004). Metal mobilization in the Gironde Estuary (France): the role of the soft mud layer in the maximum turbidity zone. *Marine Chemistry*, 87, 1–13
- Rosemary, F., Vitharana, U. W. A., Indraratne, S. P., & Weerasooriya, S. V. R. (2014). Concentrations of trace metals in selected land uses of a dry zone soil catena of Sri Lanka. *Tropical Agricultural Research*, 5(4), 412–422
- Roser, B. P., & Korsch, R. J. (1999). Geochemical characterization, evolution and source of a Mesozoic accretionary wedge: The Torlesse terrane, New Zealand. *Geological Magazine*, 136(5), 493–512

- Sparks, D. L. (2003). *Environmental soil chemistry*. (2nd ed.). Elsevier publications.
- Sposito, G. (2008). *The chemistry of soils*. Oxford University Press Inc.
- Sutherland, R. A. (2000). A comparison of geochemical information obtained from two fluvial bed sediment fractions. *Environmental Geology*, 39(3–4), 330–341
- Taylor, S. R., & McLennan, S. M. (1985). *The continental crust: Its composition and evolution*. (p. 312). Blackwell Scientific.
- Thenabadu, M. W. (1988). *Soil and soil conservation in Sri Lanka*. Natural resources energy and research authority.
- Violante, A., Cozzolino, V., Perelomov, L., Caporale, A. G., & Pigna, M. (2010). Mobility and bioavailability of heavy metals and metalloids in soil environments. *Journal of Soil Science and Plant Nutrition*, 10(3), 268–292
- Wanigasuriya, K. P., Peiris, H., Ileperuma, N., Peiris-John, R. J., & Wickremasinghe, R. (2008). Could ochratoxin A in food commodities be the cause of chronic kidney disease in Sri Lanka. *Transactions of the Royal Society of Tropical Medicine and Hygiene*, 102, 726–728
- Wickramasinghe, W.A.M.B.D. (2004). Management of rice growing soil in the dry zone. Mapa, R.B., Somasiri, S. and Dissanayake, A.R. (Eds.). Soils of the dry zone of Sri Lanka. Soil science society of Sri Lanka, Special publication, 7, 202–214.
- Wimalawansa, S. A., & Wimalawansa, S. J. (2014). Impact of changing agricultural practices on human health: Chronic kidney disease of multi-factorial origin in Sri Lanka. *Wudpecker Journal of Agricultural Research*, 3, 110–124
- Wimalawansa, S. J. (2016). The role of ions, heavy metals, fluoride, and agrochemicals: Critical evaluation of potential aetiological factors of chronic kidney disease of multifactorial origin (CKDmfo/CKDu) and recommendations for its eradication. *Environmental Geochemistry and Health*, 38, 639–678
- Young, S. M., Pitawala, A. H. M. T. G., & Ishiga, H. (2010). Factors controlling Fluoride content of ground water in North central province and North –Western Province Sri Lanka. *Environmental Earth Science*, 63(6), 1333–1342
- Young, S. M., Pitawala, A., & Ishiga, H. (2013). *Geochemical characteristics of stream sediments, sediment fractions, soils, and basement rocks from the Mahaweli River and its catchment*. Chem Erde Geochem. <https://doi.org/10.1016/j.chemer.2012.09.003>
- Yuan, X., Chen, Y., Li, B., & Siegel, D. I. (2010). Source of sediments and metal fractionation in two Chinese estuarine marshes. *Environmental Earth Science*, 60, 1535–1544.
- Zhang, J., & Liu, C. L. (2002). Riverine composition and estuarine geochemistry of particulate metals in China—weathering features, anthropogenic impact and chemical fluxes. *Estuarine, Coastal and Shelf Science*, 54, 1051–1070.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.