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FINAL REPORT

ENVIRONMENTAL AND CHILDHOOD LEAD CONTAMINATION: ROLE OF THE BOAT-REPAIR INDUSTRY IN SOUTHERN THAILAND

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ENVIRONMENTAL AND CHILDHOOD LEAD CONTAMINATION: ROLE OF THE BOAT-REPAIR INDUSTRY IN SOUTHERN THAILAND.

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Environmental and Childhood Lead Contamination: Role of the Boat-repair Industry in Southern Thailand

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ABSTRACT

The wooden-boat building and repair industry has been implicated as a potential source of human lead contamination because of the use of plumboplumbic oxide (Pb_3O_4) in the process of caulking boat hulls.

The objective of this study was to examine the patterns of environmental and childhood lead contamination in relation to distance and direction from local boatyards, and to identify the factors influencing the distribution of environmental and childhood lead contamination in an area surrounding boat-repair yards where plumboplumbic oxide is used.

A cross-sectional spatial study design was employed in a residential area extending approximately 5 kilometres along the coast and including 3 large boat-repair yards in Tambol Hua Khao, Singhanakhon District, Songkhla Province, on the east coast of peninsular Thailand.

Three hundred and thirty children aged between 4 and 14 years resident in the study area who had received parental consent were randomly selected. Home visit and interview of the parents or guardians obtained information regarding environment-contact child behaviour and occupation and activities of members of each child's household. Venous blood specimens were taken from 318 of these children and dust specimens collected from an undisturbed position in each household. Soil specimens were obtained from the interstices of a square grid pattern superimposed on a map of the study area. Geographic coordinates of

children's\residence and soil sampling positions were recorded and mapped. Kriging and contouring were used to describe the spatial distribution of lead in dust and soil and these environmental levels modeled in terms of distance and direction from a boatyard and, for dust, also occupation of household members in boat-repair work and home condition. Childhood blood lead levels were modeled in terms of environmental lead levels and environment-contact behaviour and occupational practices associated with boat-repair of household members.

Household dust lead content and soil lead content ranged from 10 to 3,025 mg/kg and from 10 to 7,700 mg/kg, respectively. The distribution of soil lead peaked approximately at the location of boatyards but outside and away from the boatyards the distribution was irregular. Household dust lead content significantly decreased with increasing distance from boatyards at a rate of 7% to 14% per 100m depending on direction and boatyard. Where a family member was a worker in one of the major boatyards and in houses where occasional repair of small boats was undertaken, household dust lead levels were significantly elevated, by 65 percent (95%CI: 18 - 131 percent) and 31 percent (95%CI: 5 - 63 percent) respectively.

Children's blood lead levels ranged from 2 to 36 µg/dl, with 52 percent higher than 10 µg/dl. Blood lead levels were highly significantly related to the levels of lead in household dust ($P < 0.00005$), increasing about 10 percent (95%CI: 5 - 14 percent) for a doubling in dust lead level, but were not found to be related to the interpolated values of soil lead at the location of the household. However, playing on the ground in front of the house was related to a 20 percent (95%CI:

9 - 32 perdent) increase in blood lead levels, and sleeping close to the floor instead of a mattress or bed elevated blood lead by up to 50 percent (95%CI: 9 - 83 percent). There was no significant relationship between childhood blood lead and household location after adjusting for household dust lead, but dust lead itself increased significantly with closer proximity to a boatyard. Statistical modeling indicated that the range of household dust lead levels may include levels above 150 mg/kg for up to at least 2.8 kilometres from a boatyard.

It is concluded that closer proximity of a household to a boatyard and occupation of a family member in boat-repair work are associated with an elevated content of household dust lead. Household dust lead, in turn, closely influences the level of lead in the blood of children in the household. Children's level of lead contamination is also elevated among those who play on the ground in front of the house where shoes are removed and among those who sleep close to the floor. Siting of boat-repair yards at a distance from residential areas, measures to reduce the spread of lead-containing dust, and education of local communities to avoid risky child behaviour are recommended to alleviate the problem of elevated childhood lead levels.

การปนเปื้อนตะกั่วในเด็กและสิ่งแวดล้อม: บทบาทของอุตสาหกรรมการซ่อมเรือในภาคใต้ของประเทศไทย

บทคัดย่อ

อุตสาหกรรมการต่อเรือ และซ่อมเรือประมงที่มีการใช้เสน (ตะกั่วแดง, lead oxide or plumboplumbic oxide (Pb_3O_4)) เป็นส่วนประกอบในกระบวนการตอกหมันเรือ มีส่วนเกี่ยวข้องกับการปนเปื้อนสารตะกั่วในคนและสิ่งแวดล้อม วัตถุประสงค์ของการศึกษาในครั้งนี้เพื่อหารูปแบบการปนเปื้อนตะกั่วในเด็กและในสิ่งแวดล้อม โดยพิจารณาถึงระยะและทิศทางจากคานเรือ และหาปัจจัยที่มีอิทธิพลต่อการแพร่กระจายสารตะกั่วในเด็กและสิ่งแวดล้อมบริเวณรอบๆอู่ซ่อมเรือที่มีการใช้เสน

การศึกษาครั้งนี้ใช้วิธีการศึกษาแบบตัดขวางเชิงพื้นที่ โดยทำการศึกษาในบริเวณชุมชนตามแนวชายฝั่งปากทะเลสาบสงขลา ระยะทางประมาณ 5 กิโลเมตร ในเขต ต.หัวเขา อ.สิงหนคร จ.สงขลา ซึ่งมีคานเรือตั้งอยู่ 3 คาน ทำการสุ่มเด็กนักเรียนอายุระหว่าง 4 ถึง 14 ปี ที่ได้รับอนุญาตจากผู้ปกครอง จำนวน 330 คน และสามารถเก็บตัวอย่างเลือดจากเด็กนักเรียนได้ 318 คน ทำการเก็บข้อมูลโดยการเยี่ยมบ้านและการสัมภาษณ์ผู้ปกครองเกี่ยวกับพฤติกรรมการสัมผัสสิ่งแวดล้อมของเด็ก อาชีพและพฤติกรรมของสมาชิกในครอบครัว เก็บตัวอย่างฝุ่นจากบริเวณที่มีการรบกวนน้อยภายในบ้านของเด็กที่เก็บตัวอย่างเลือดแล้ว เก็บตัวอย่างดินจากจุดเก็บที่ได้กำหนดบนแผ่นที่เป็นตารางสี่เหลี่ยมบนแผ่นที่ครอบคลุมทั้งพื้นที่ศึกษา และทำการบันทึกตำแหน่งพิกัดทางภูมิศาสตร์ของบ้านและจุดเก็บตัวอย่างดิน วิเคราะห์หารูปแบบการแพร่กระจายของสารตะกั่วในดินและฝุ่นด้วยวิธีคริกิ้ง หาปัจจัยที่มีผลต่อระดับตะกั่วในฝุ่นโดยใช้สมการสหสัมพันธ์ถดถอยเชิงเส้นตรง โดยคำนึงถึงระยะและทิศทางจากคานเรือ อาชีพของสมาชิกภายในครอบครัว และสภาพโดยทั่วไปของบ้าน วิเคราะห์หาปัจจัยที่มีผลต่อระดับตะกั่วในเด็กโดยใช้ระดับตะกั่วในสิ่งแวดล้อม พฤติกรรมของเด็ก และพฤติกรรมของสมาชิกภายในครอบครัวที่เกี่ยวกับการซ่อมเรือ

ผลการศึกษา ระดับตะกั่วในตัวอย่างฝุ่นจากบ้านเรือนและตัวอย่างดินพบว่ามีค่าระหว่าง 10 ถึง 3,025 มิลลิกรัมต่อกิโลกรัม และ 10 ถึง 7,000 มิลลิกรัมต่อกิโลกรัม ตามลำดับ ระดับตะกั่วในดินมีค่า

สูงในบริเวณคานเรือและบริเวณที่ห่างจากคานเรือเป็นบางแห่ง สำหรับระดับตะกั่วในฝุ่นมีค่าลดลงอย่างมีนัยสำคัญ เมื่อระยะห่างจากคานเรือเพิ่มขึ้นทุกๆ 100 เมตร โดยจะลดลงระหว่าง 7 ถึง 14 เปอร์เซ็นต์ ขึ้นกับทิศทางจากคานเรือ และพบว่าบ้านที่มีสมาชิกในครอบครัวทำงานเกี่ยวข้องกับการซ่อมเรือ จะมีระดับตะกั่วในฝุ่นสูงขึ้นอย่างมีนัยสำคัญ โดยจะเพิ่มขึ้น 65 เปอร์เซ็นต์ (95 %CI: 18 – 131 เปอร์เซ็นต์) ในบ้านที่มีสมาชิกทำงานในคานเรือ และ 31 เปอร์เซ็นต์ (95%CI: 5 – 63 เปอร์เซ็นต์) ในบ้านที่มีสมาชิกซ่อมเรือหางยาว

ระดับตะกั่วในเด็กกลุ่มตัวอย่างพบว่ามีค่าอยู่ระหว่าง 2 ถึง 36 ไมโครกรัมต่อเดซิลิตร และพบว่า 52 เปอร์เซ็นต์ ของเด็ก มีระดับตะกั่วในเลือดสูงกว่า 10 ไมโครกรัมต่อเดซิลิตร เมื่อวิเคราะห์ทางสถิติพบว่าระดับตะกั่วในเด็กมีความสัมพันธ์กับระดับตะกั่วในฝุ่นอย่างมีนัยสำคัญยิ่ง ($p > 0.00005$) โดยระดับตะกั่วในเด็กจะเพิ่มขึ้นประมาณ 10 เปอร์เซ็นต์ เมื่อระดับตะกั่วในฝุ่นเพิ่มขึ้น 2 เท่า (95%CI: 5 – 14 เปอร์เซ็นต์) แต่ไม่พบความสัมพันธ์ระหว่างระดับตะกั่วในเด็ก และระดับตะกั่วในดินที่ได้จากการประมาณค่าตรงตำแหน่งของบ้าน อย่างไรก็ตามพบว่าเด็กที่เล่นบนพื้นหน้าบ้าน จะมีระดับตะกั่วสูงขึ้น 20 เปอร์เซ็นต์ (95%CI: 9 – 32 เปอร์เซ็นต์) ส่วนเด็กที่นอนบนพื้นหรือบนเสื่อ จะมีระดับตะกั่วเพิ่มขึ้น 50 เปอร์เซ็นต์ (95%CI: 9 – 83เปอร์เซ็นต์) เมื่อเปรียบเทียบกับเด็กที่นอนบนฟูกหรือบนเตียง ส่วนตำแหน่งที่ตั้งของบ้านพบว่าไม่มีความสัมพันธ์ระดับตะกั่วในเด็กเมื่อมีการปรับค่าด้วยระดับตะกั่วในฝุ่นแต่ระดับตะกั่วในฝุ่นจะเพิ่มขึ้นอย่างมีนัยสำคัญเมื่อระยะห่างจากคานเรือลดลง จากแบบจำลองทางสถิติพบว่าระดับตะกั่วในฝุ่นจากบ้านจะลดลงถึง 150 มิลลิกรัมต่อกิโลกรัม เมื่อบ้านและคานเรือมีระยะห่างอย่างน้อยที่สุด 2.8 กิโลเมตร

การศึกษานี้สามารถสรุปได้ว่าระยะห่างระหว่างคานเรือกับบ้านและอาชีพของสมาชิกในครัวเรือนที่เกี่ยวข้องกับการซ่อมเรือ มีความสัมพันธ์กับการเพิ่มขึ้นของระดับตะกั่วในฝุ่นจากบ้านเรือน และระดับตะกั่วในฝุ่นมีความสัมพันธ์เป็นอย่างยิ่งกับระดับตะกั่วในเด็ก นอกจากนี้ เด็กกลุ่มที่เล่นบนพื้นหน้าบ้านซึ่งเป็นบริเวณที่ถอดรองเท้า และเด็กที่นอนบนพื้น จะมีระดับตะกั่วในเลือดสูง ดังนั้น ตำแหน่งที่ตั้งของคานเรือที่ห่างจากชุมชน การมีมาตรการลดการแพร่กระจายของฝุ่นที่ปนเปื้อนตะกั่ว และการให้การความรู้แก่ชุมชนเพื่อหลีกเลี่ยงพฤติกรรมเสี่ยงของเด็ก จะสามารถบรรเทาปัญหาการเพิ่มขึ้นของระดับตะกั่วในเด็กได้

ENVIRONMENTAL AND CHILDHOOD LEAD CONTAMINATION: ROLE OF THE BOAT-REPAIR INDUSTRY IN SOUTHERN THAILAND.

Executive summary

Lead contamination in human can cause serious adverse health effects, especially in children. Long-term exposure to low levels of lead has been linked to impaired neurological development, disturbed heam synthesis and interference with metabolism of Vitamin D. Dust and soil have been identified as significant contributors to lead exposure in humans in several different settings.

The boat-building and repair industry in Thailand has been identified as a potential source of environmental lead contamination. Children living at the mouth of Pattani river in Muang District, Pattani Province, have been found to have higher than normal blood lead levels and a distribution which peaked in the region of a boat-repair yard. The process of construction and repairing wooden boats involves the use of plumboplumbic oxide (Pb_3O_4). This substance is supplied in powder form for mixing in the caulking materials and, if used without adequate precautions, is difficult to confine to the immediate work site. It is estimated that there are 220 major boat construction and repair yards in Thailand, with approximately 70 yards in the southern region. The cumulative potential of these boatyards for contaminating the coastal environment and local communities could be considerable.

This study aimed to examine the patterns of environmental and childhood lead contamination in relation to distance and direction from local boatyards, and identify the factors influencing the distribution of

environmental and childhood lead contamination in the area surrounding boatyards where plumboplumbic oxide is used. A cross-sectional spatial study design was employed in a residential area extending approximately 5 kilometres along the coast and including 3 large boat-repair yards in Tambol Hua Khao, Singhanakhon District, Songkhla Province, on the east coast of peninsular Thailand.

Three hundred and eighteen children aged between 4 and 14 years resident in the study area for at least one year were randomly selected and a blood specimen collected for determination of lead level. Household dust specimens were collected from the residence of each child. Soil specimens were obtained from the interstices of a square grid throughout study area. The position of each household and soil sampling positions were recorded and data on child-environment-contact behaviours, occupation and practices of household members and others potential influencing factors were collected by interviews of parents and children and by direct observation. Spatial analytical methods and multivariate regression modelling were used to analyze these data. The study protocol was approved by the ethics review committee of the Faculty of Medicine, Prince of Songkla University.

Soil lead was high at the location of boatyards but outside and away from the boatyards the distribution was irregular. The distribution of household dust revealed lead high levels clustered in areas close to the boatyards and some sparsely distributed at distances from the boatyards. Regression modelling showed that household dust lead content significantly decreased with increasing distance from the boatyards. Where a family member was a worker in one of the major boatyards and in houses where occasional repair of small boats was undertaken, household dust lead levels were significantly elevated. Blood lead levels were equal to or exceeded 10 µg/dl in 50 percent of the children. Blood lead levels were significantly related to the levels of lead in household dust, but were not found to be related to the interpolated values of soil lead at the location of the household. However, playing on the ground in front of the house where shoes are removed and sleeping close to the floor instead of on a mattress or bed were significantly related to elevated blood lead levels. There was no significant relationship between childhood blood lead and household location after adjusting for household dust lead, but dust lead itself increased significantly with closer proximity to a boatyard. Regression modelling indicated that the range of household dust lead levels may include levels above 150 mg/kg for up to at least 2.8 kilometres from a boatyard.

It is concluded that closer proximity of a household to a boatyard and occupation of a family member in boat-repair work are associated with an elevated lead content in household dust. Household dust lead, in turn, closely influences the level of lead in the blood of children in the household. Children's blood lead level is also elevated among those who play on the ground the shoe-removal area in front of their house and among those who sleep close to the floor. Siting of boat-repair yards at a distance from residential areas, measures to reduce the spread of lead-containing dust, and education of local communities to avoid risky child behaviour are recommended to alleviate the problem of elevated childhood lead levels in this setting.

Acknowledgement

I would like to express my thanks to the subjects and their guardians in Tambol Hua Khao, Amphoe Singhanakhon, Songkhla, for their willing cooperation, and to all teachers in HuaKhao School, Bosap School and Khaodaeng School, who helped me during data collection.

I am indebted to my supervisor Dr Alan Geater for his considerable tuition and kind help throughout the completion of the thesis. I would like to acknowledge Prof. Dr Virasakdi Chongsuvivatwong who provided valuable suggestion and support throughout my study period.

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I would like to express my appreciation to the Thailand Research Fund (through a Royal Golden Jubilee award to Dr Alan Geater and a Basic Research Grant Program) and a research grant from the Graduate School, Prince of Songkla University.

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Nipa Maharachpong

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Abbreviations and Symbols

CDC	Centers for Disease Control and Prevention (USA)
CI	Confidence interval
EPA	Environmental Protection Agency (USA)
FAA	Flame atomic absorption
PbB	Blood lead
PbD	Household dust lead
PbS	Soil lead
SD	Standard deviation
UTM	Universal Transverse Mercator
µg/dl	Microgram per decilitre
mg/kg	Milligram per kilogram

Chapter 1: Introduction

Lead contamination in human can cause serious adverse health effects, especially in children. Long-term exposure to low levels of lead has been linked to impaired neurological development, disturbed heam synthesis and interference with metabolism of Vitamin D. Dust and soil have been identified as significant contributors to lead exposure in humans in several different settings[1-5].

The boat-building and repair industry in Thailand has been identified as a potential source of environmental lead contamination. Children living at the mouth of Pattani river in Muang District, Pattani Province, have been found to have higher than normal blood lead levels. Mean blood lead of children within geographic clusters closely followed the patterns of soil and household dust lead throughout the area, and all specimen types showed a spatial distribution which peaked in the region of a boat-repair yard[6]. The process of caulking wooden boats involves the use of plumboplumbic oxide (Pb_3O_4). This substance is supplied in powder form and, if used without adequate precautions, is difficult to confine to the immediate work site. It is estimated that there are 223 major boat construction and repair yards in Thailand, with 70 in the southern region[7]. The cumulative potential of these boatyards for contaminating the coastal environment and local communities could be considerable.

1.1 Literature review

The effects of chronic lead contamination of children include impaired neurological development, disturbances of haem synthesis and vitamin D metabolism. These effects can develop after long-term exposure to low levels of lead, during the early stages of which there may be few or no overt signs or symptoms of lead poisoning.

Scenarios in which human lead contamination has been reported generally involve the production, use or disposal of lead-containing material, either in the form of metallic lead or as lead compounds. Thus human contamination has been associated with the extraction of lead ore[8-10], smelting of lead[11-13], the manufacture of lead batteries[14-16]; with the use of lead-containing paint[17-19], leaden water pipes[20], and leaded petrol[21-23]; with battery dumps[24] and lead-mines[4] and tin-mine waste[6;25] and waste dumps[26;27]. In general, contamination associated with the use of lead-containing materials is rather widespread, whereas that associated with manufacturing processes or waste dumps is more localized. Depending on the particular circumstances, however, human contamination may be relatively direct or may involve the dispersal of lead from the source into the surrounding environment, whence human uptake occurs.

1.1.1 Contamination patterns

The dynamics of contamination scenarios involving a dispersal stage are relatively complex, as they involve the movement of the contaminant into the surrounding environment, its movement and possible change of form within the environment, and the various pathways via which humans end up becoming contaminated.

The patterns of environmental lead contamination surrounding point sources of lead have been described for a number of situations[26;29;29]. Such patterns may be expected to be situation-specific, although all probably involve spatial, temporal and climatic factors. Uptake by humans is also variable, depending largely on the form and amount of lead in which occurs in the proximate source, but also on age and environment-contact behaviour patterns.

The principal routes of lead contamination in human are via the digestive tract, respiratory system and absorption through the skin, although the latter pathway is largely confined to organic lead, such as tetra-ethyl lead which formerly was used as an additive to petrol.

Environmental compartments to which, and in which, lead can be dispersed include air, soil, sediment, surface water, ground water and biota. Lead in the atmosphere is emitted, mostly in particulate form, from automobile exhaust, smelters and mines, and may be subsequently deposited as dust or onto soil and water. Generally, lead is strongly adsorbed onto particles of soil, dust and sediment because lead has tendency to form compounds of low solubility in natural water[30].

Dust and soil have been identified as most significant contributors to lead exposure in humans in a number of different settings[1;3;4;31]. The ingestion of lead in dust or soil via dirty hands has frequently been suggested to be an important pathway[32-35]. This is partially because lead is associated with the smallest particle sizes, which are difficult to detect and remove[1;36;37]. A meta-anlaysis of the contribution of house dust and residential soil to children's blood lead levels using a pooled analysis of 12 epidemiologic studies concluded that lead-contaminated house dust is the major source of lead-exposure for children, and further demonstrated a strong relationship between interior dust loading and children's blood lead levels[38]. However, in a tropical setting such as in Thailand, where houses are generally open and where children frequently play outside the house, childhood exposure to lead in soil could be as important as that to lead in household dust.

It has been suggested that, in some settings, family members act as significant contributors to the lead burden of children[24;39;40]. This was shown in a study of the Broken Hill lead mining community in New South Wales, Australia, where fathers who were engaged in mining occupation were the major contributors to their children's lead contamination[41].

Childhood blood lead levels are influenced not only by ambient environmental lead levels but also by the degree of environment-contact behaviour exhibited by the children. Thus modification of behaviour may be expected to be reflected in alterations over time in a child's body lead burden. A prospective environmental intervention study was conducted to determine the impact of reduction of risk-activities among children with mildly elevated PbB levels[42]. The one-time intervention focused mainly on cleaning and repainting window areas and education of caregivers to maintain effective housekeeper techniques. The hazard-reduction activities were associated with a modest decline in blood lead levels among children with severe hazards[42]. Such findings underline the potential value of providing relevant information, and of fostering appropriate attitudes and practice, in any quest to prevent lead exposure of children.

1.1.2 Biological fate of lead

Lead is primarily distributed in the body in three compartments -- blood, soft tissue, and mineralizing tissue. The body accumulates lead over a lifetime and normally releases it very slowly. Mineralizing tissues contain about 95% of total body burden of lead in adults[43]. Of the lead in the blood, 99% is associated with erythrocytes; the remaining 1% is in the plasma, where it is available for transport to the tissues[43]. Adsorption of ingested lead occurs in the small intestine and is affected by a variety of factors, such as its chemical and physical form and the physiologic characteristics of the exposed person (e.g. age, nutritional status and dietary type). The quantity absorbed increases significantly under fasting conditions and dietary deficiency of essential elements such as iron, calcium, zinc, copper, and phosphorus[44].

The biological effects of lead are mediated by interference with enzyme systems due to binding of lead with -SH group of protein and the replacement of other essential metal ions. Reported effects include retarded neurological development[45], retarded physical development[46], decreased haem biosynthesis[47,48] and decreased serum level of vitamin D[49]. Whether lead enters the body through inhalation or ingestion, the biologic effects are the same. The neurotoxicity of lead is of particular concern, because evidence from many investigations indicates that neurobehavioral effects[50], such as intellectual deficit[16] and deficits in skills such as speech and language processing, attention and hearing, may persist even after PbB levels have returned to normal[51].

1.1.3 Spatial interpolation

Studies of lead contamination in human and environment have mostly investigated just the level of lead in samples, combined with a descriptive evaluation of the source lead pollution, and the pattern of lead contamination has been limited [52]. To date, however, there are a few surveys of environmental pollution concerning the spatial distribution of lead contamination especially contamination in soil[53]. Information on spatial distribution of lead contamination is important, as this may provide both an estimate of the concentration at a given unsampled location, as well as an estimate of the probability that the concentration at the location will exceed a critical threshold concentration. There are several methods for estimating unsampled positions, as outlined below.

Theissen polygons(Voronoi polygons, Dirichlet tesselation)

This method is one of the earliest and simplest proximal interpolation methods. The region sampled is divided by perpendicular bisectors between the sampling points into polygons or tiles, such that in each polygon all points are nearer to its enclosed sampling point than to any other sampling point. The prediction at each point in the polygon is the measured value at sampling point[54].

The shortcomings of the method are evident; each prediction is based just one measurement, there is no estimate of the error, and information from neighboring points is ignored. When used for mapping the result is crude; the interpolated surface consists of a series of steps.

Triangulation

This is one of the simplest interpolation methods. The sampling points are linked to their neighbours by straight lines to create triangles that do not contain any of the points. There are several triangulation methods, including linear triangulation weighted average of the three observation values, and polynomial fitting within each triangle in the triangulation.

The disadvantages are that, although it is somewhat better than the Thiessen method, each prediction still depends on only three data points; it makes no use of data further away, and there is no measure of error. Unlike the Theissen method, the resulting surface is continuous, but the surfaces are not smooth, caused by discontinuous slopes at the triangle edges and data points[54].

Inverse distance weighting

Inverse functions of distance methods are based on the assumption that the interpolated surface should be influenced most by the nearby points and less by the more distant points. The interpolating surface is a weighted average of the scatter points and the weight assigned to each scatter point diminishes by distance. The most popular choice is the inverse weighting by squared distance. An interactive feature of the inverse square distance is that the relative weights diminish rapidly as the distance increases, and so the interpolation is sensibly local; further, because weights never become zero there are no discontinuities[54].

The disadvantages of this method are the choice of weighting function is arbitrary and also there is no measurement of error. Further, it takes no account of the configuration of sampling. So, where data are clustered two or more may be at approximately the same distance and direction from the estimated point and each point will carry the same weight as an isolated point a similar distance away but in different direction.

Kriging method

Kriging is an optimal geostatistical method for spatial interpolation, which provides a solution to the problem of estimation based on a continuous model of stochastic spatial variation. The basis of this technique is the rate at which the variance between points changes over the space, expressed in the variogram which shows how the average difference between values at points changes with distance between points. There are several variations of kriging, both linear and non-linear. Ordinary kriging is the one most used and robust type of linear kriging in practice which uses a weighted linear combinations of a number of neighbourhood sample values to model the spatial variation within the local area bounded by the input sample points.

Kriging has been elaborated to tackle increasingly complex problems in mining, pollution control and abatement, and public health[54;55]. Kriging itself is a statistical weighted technique which considers the spatial continuity pattern by plotting the variation between sampling points separated by a given distance and direction, called a "variogram".

The variogram is a graphical presentation of the average squared difference between sampling points as a function of distance and direction. The variogram is defined by

$$\gamma(h) = \frac{1}{2N}\sum_{i=1}^{n}[g(x) - g(x+h)]^2$$

Where

$\gamma(h)$ denotes the observational semi-variogram.

h is the distance between two samples, (lag).

g(x) is the value of variable taken at location x.

g(x+h) is the value of variable taken at location x+h.

n is the number of pairs of g(x) and g(x+h).

i is a pair number, i > 0 and $i \leq n$

The expected form of the variogram is that γ should increase as h increases. This is on the basis of points that are close together should be more similar than points that are widely separated. Eventually a lag(h) is reached, above which γ does not increase, called the "sill" at lag(h) called "range". The intersection with the y-axis is called "nugget". A non-zero nugget indicates that repeated measurements at the same point give different values.

1.1.4 Spatial interpolation of lead contamination

Investigations of lead contamination in the environment have mostly examined the concentrations which exceed threshold levels but the area of contamination is not precisely known. The spatial interpolation of contamination could fill this gap, by providing probabilistic evaluation of lead levels in unsampled locations. Mapping of lead contamination also gives immediate appreciation of the change in the contamination with space and enables the identification of risky areas. This information could provide decision-making power that is needed for an abatement programme to reduce lead contamination in humans. A few studies have made serious attempt to construct the spatial distribution of lead contamination[53]. A search of the electronic databases, PubMed, Science-direct, Springer-link and Google Scholar, for articles published since 1994 using the keyword "spatial interpolation", "lead" and "soil" yielded the studies shown in Table 1.1

Table 1.1 The spatial interpolation of lead contamination in soil.

Reference	Objective	No. samples	Method	Setting & location
Ersoy et al.(2004)[55]	To determine the extent and magnitude of Pb levels	329	kriging	Abandoned mine, Derbyshire, UK
Lin et al.(2002)[56]	To characterize and map the spatial variability patterns of seven heavy metals in soil	194	Kriging	Rice paddy field, Taiwan
Cattle et al. (2002)[57]	To delineate contaminated area	807	Kriging	Inner-Sydney suburb of Glebe, Australia
Purohit et al.(2001)[58]	To determine the distribution of heavy metals	398	Inverse square distance	City highways, India
Facchinelli, et al(2001)[59]	To identify the sources of heavy metal in soil	50	Kriging	Road transport, industrial areas, Italy
Shinn et al.(2000)[60]	To model and estimate soil Pb levels in an urban and residential neighborhood	62	Kriging	Light industry and busy street, Chicago, USA
Meilke,et al (1999)[61]	To determine the association between soil Pb and blood Pb	4026	Inverse square distance	Parental materials, New Orleans, Louisiana, USA

Table 1.1 (continued)

Reference	Objective	No. samples	Method	Setting & location
Leonte and Schofield (1996)[62]	To evaluate the soil contaminated site and clean-up criteria	335	Kriging	Old dumps of domestic and industrial residues, Australia
Piotrowska,et al(1994)[63]	To determine the distribution of Pb in agriculture soil	1060	Inverse distance	Agricultural area, Poland
Atteia,et al(1994)[64]	To identify the distribution of trace metals	366	Kriging	Fertilizer or domestic waste, Swiss Jura

Most studies on the spatial distribution of lead contamination in the environment have interpolated secondary data using kriging or inverse squared distance methods. An increasing number of studies have used kriging to describe the spatial distribution of lead but some of those did not specify the variogram model, variogram parameter[60] (range, sill and nugget effect) or type of kriging used[59]. However, the performance of kriging, inverse distance weighted and other interpolation methods has been reported to differ only little in most settings[65] and the choice of interpolation method might best depend on the distribution of data points, the quality of interpolation needed, the skill of researcher and computing power[66].

Nevertheless, nowadays, the number of studies using spatial analysis is increasing but few studies have been concerned with the relationship of human health and spatial distribution of lead contamination obtained from the interpolation methods. Only one of the 10 studies in Table 1.1 concerns human health. Mielke[61] investigated the relation between spatial distribution of environmental lead and children's health by categorizing the area of lead contamination into high metal and low metal areas, defined by interpolation using the inverse distance weighted method.

The studies reported in this thesis are an attempt to interpolate the distribution of lead contamination in soil and household dust, and relate this spatial distribution with childhood blood lead levels in the vicinity of boat-repair yards.

1.2 Situation analysis and rationale

Evidence of lead contamination has been found in Pattani province, on the east coast of peninsular Thailand, among children living in the Pattani River basin[6]. Two major foci of contamination were identified: in the region of abandoned tin-mines at the headwaters of the river, and in Pattani town at the mouth of the river[6]. The source of lead contamination in the former area has been clearly shown to the dumps of mine-waste left exposed in the area since the mines closed some 15 years previously[25]. In the latter area, however, the source of lead contamination was not so clearly identifiable. It has been suggested that tin-mine waste washed down in the water current and deposited at the mouth of the river is a major source.

More recently, however, an alternative potential source of lead contamination at the river mouth was identified. Three boat repair yards in the area were found to be using Pb_3O_4 for mixing in the caulking material used to build and repair wooden boats. Considerable circumstantial evidence has been presented to support the contention that this industry may indeed be an important contributor to environmental and human lead contamination in this area. It was shown, for example, that soil, household dust and children's blood lead levels closely paralleled each other throughout the area and each showed increasing levels as the location of a boatyard was approached[6]. Furthermore, a survey of workers engaged in various occupations in Pattani town showed boatyard workers to have higher blood lead levels (PbB) than other workers, and those boatyard workers who were responsible for caulking had the highest PbB's of all[67].

Field observations have revealed that handling of lead oxide in boat-repair yards on the Pattani River was very casual, with considerable spillage onto the ground and working surfaces, from where it could readily be distributed to the surrounding areas. Workers are likely to inhale lead dust during mixing of caulking materials, and have been observed eating and drinking in and around the workplace, increasing the probability of lead ingestion. It is likely also that workers may carry lead dust home on their skin, shoes and clothes, thus inadvertently exposing family members. Moreover, children were frequently observed playing in the boatyards. Young children have a greater potential for lead contamination, and are especially susceptible to its toxic effects.

Nevertheless, conclusive evidence that the boat-repair industry is a significant contributor to environmental and childhood lead contamination, and information on the magnitude of contamination from this source, are still lacking. This situation has two important implications. First, if an effective lead contamination abatement programme is to be implemented in the known high childhood contamination region at the mouth of Pattani River, it is essential that the relative contributions of the boat-repair industry and mining waste to total lead contamination first be determined. Second, the fact that there are some 70 boatyards[7] scattered around the coast of southern Thailand, many located adjacent to residential communities, suggests that, if the industry is indeed a source of lead pollution, quite large numbers of children living in the coastal region of southern Thailand may be at risk of contamination.

This study proposes to address the spatial distribution of lead contamination of the environment and children in a different coastal region, where there is no influence of mining activities, and to confirm whether boat-repair yards are acting as point sources of environmental and human lead contamination.

The relationship between individual levels of human contamination and environmental lead levels and the spatial relationship to the site of ultimate source, however, are greatly influenced by behaviours relating to human or environment contact. In addition, a number of proximate source in the household might also exist, such as used batteries, lead-lined water storage tank, lead sinkers for fishing nets.

The expected impact of the study is the provision of baseline information of the influencing factors related to spatial distribution of lead after adjusting for biological factors and environment-contact behaviours. This information should enable informed decisions to be made regarding the need for, and nature of, any specific lead contamination risk-abatement programme regarding this particular industry.

1.3 General research question

What is the spatial pattern of lead contamination in the environment and in children in the area surrounding boat-repair yards where plumbo-plumbic oxide is used?

1.4 Objectives

1. To assess the evidence for a spatial association between soil and dust lead content and the location of boat-repair yards in the study area.

2. To assess the evidence for a spatial association between childhood blood lead levels and the location of boat-repair

yards after adjusting for household condition, environment-contact behaviour, and other sources of lead uptake.

3. To identify the probable proximate sources and risk behaviour for childhood lead contamination and the magnitude of their contribution to childhood blood lead levels.

Chapter 2: General methodology

This chapter contains details of the general methods and methodology employed in this study. Further details pertaining to particular aspects of the study are given in subsequent chapters dealing with specific issues. The study was approved by the Ethics Committee of the Faculty of Medicine, Prince of Songkla University.

2.1 Study site

The area located on the western coast of the mouth of Songkhla Lagoon, in Singhanakhon District, Songkhla Province (Figure 2.1) was selected for examining the spatial distribution of environmental lead level and childhood lead contamination. This area offered several features rendering it an amenable study site for those purposes.

1. There were 3 large boat-repair yards situated in the area, each of the yards adjacent to a residential community.

2. The communities of the area were served by 3 primary schools.

3. The habitable area forms a relatively narrow strip, from 150 to 500 meters wide approximately, running between the hills and the shore of the lake. This restricted area was expected to simplify the spatial analysis.

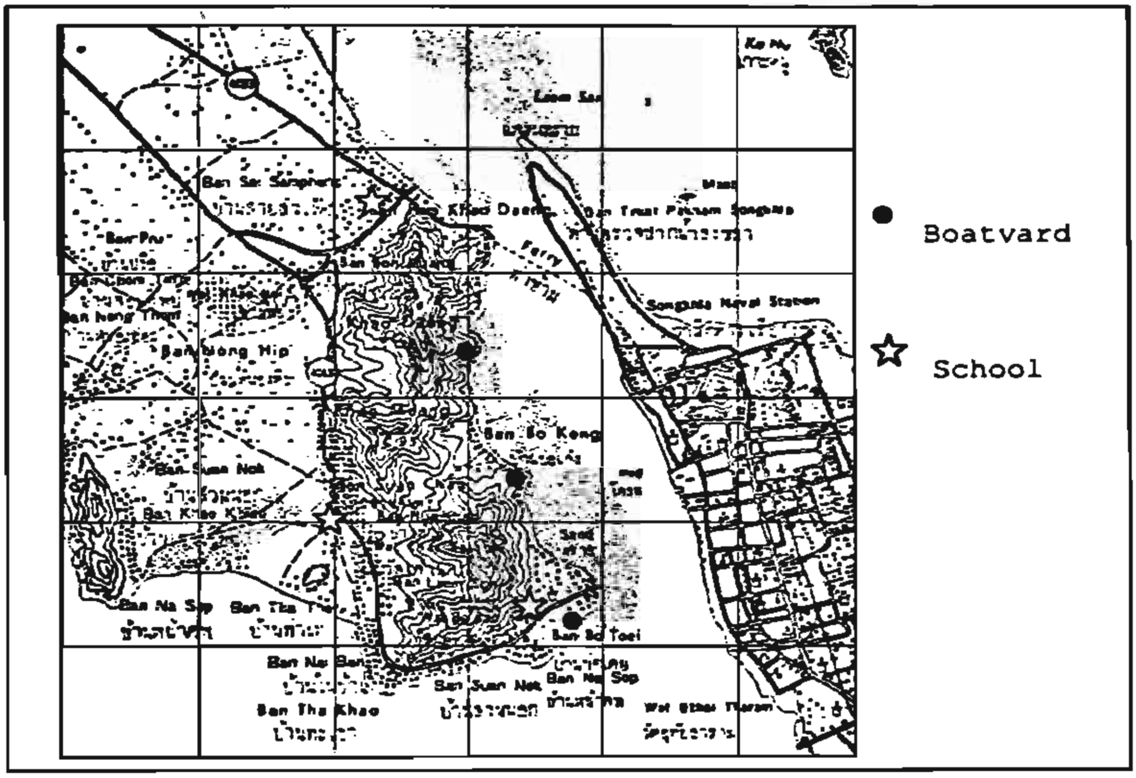
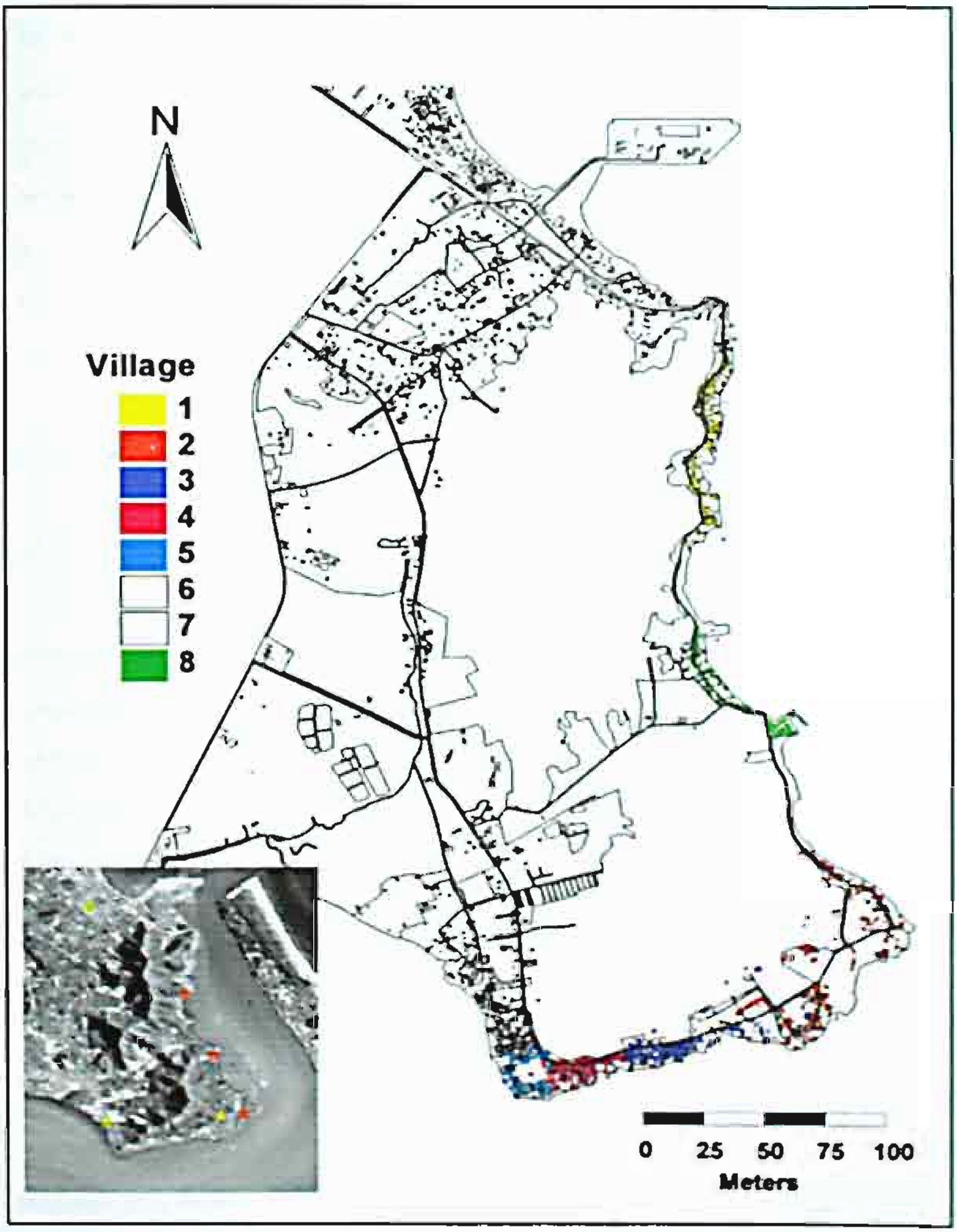


Figure 2.1 Map of the study area, Hua Khao Sub-district, Singhanakhon District, Songkhla Province.

The area comprised most of the Hua Khao Sub-district of Singhanakhon District. Of the 8 villages in this sub-district, six, namely villages 1 (part only), 2, 3, 4, 5 and 8, fell within the study area. The approximate population size of each of these villages (or part of village for village 1) were 1,800, 1,250, 1,530, 1500, 1,120 and 600, respectively. Overall, about 80 percent were Muslim and 20 percent Buddhist. Villages 1, 4 and 5 were predominantly Muslim, village 3 mixed and villages 2 and 8 predominantly Buddhist. Major occupations throughout the sub-district were fishery, boat-repair and casual labour. Socio-economic status was generally low and housing mostly crowded.

Figure 2.2 Map of the study area. Villages 1, 2, 3, 4, 5 and 8 of Hua Khao Sub-district, Singhanakhon District, Songkhla Province.



The three boat-repair yards, subsequently referred to as boatyards 1, 2 and 3, were located in villages 2, 8 and 1, respectively. They had been in operation, respectively, for about 20, 40 and 20 years and had the capacity for repairing between 25 to 30, 5 to 10 and 15 to 20 boats per month. Each boatyard caulked wooden fishing boats in the same general way, that is by hammering cotton fibre mixed with plumboplumbic oxide (red lead) powder between the wooden planks, followed usually by pressing in a putty made from a mixture of a natural oil, powdered dammar resin, red lime and plumboplumbic oxide.

2.2 Child study sample

Children aged between 4 to 14 completed years on 15th February 2001, resident in Tambol Hua Khao, within 2 kilometers of any boatyards were selected by using village as the unit of computation. Villages 1, 2, 3, 4, 5 and 8 were included as the study area (Figure 2.2). A list of children was compiled from the registration records of 3 primary schools serving the tambol. As the registered address of some children differed from the true address, the latter was confirmed with the assistance of teachers, health workers and local health volunteers.

Informed consent was sought from the parents or guardians of each eligible child through a letter distributed by the staff of each school. Children who for any reason would be at risk of adverse effect of drawing blood, or who were ill during the sampling period, were excluded from the sampling protocol. From those giving consent, a random sample was drawn from a combined list of all children stratified on village of residence, with the sampling fraction dependent on the proximity of the village to a boatyard.

2.2.1 Child sample size

No fully appropriate method exists for calculation of sample size in this spatial study. Instead sample size was based on a comparison that is less powerful to see the relationship between site and childhood blood of environmental lead level. The calculated sample size should then be more than adequate for the planned analysis.

Sample size was based on the power to detect a difference in PbB between children resident within 1 km of a boatyard and those living more distant of at least 1.25 times. Because distributions of PbB were expected to be skewed to the higher levels, calculations were based on the logarithm transformed PbB in µg/dl. Using the data from Pattani study to approximate values of geometric standard deviation (approximately 1.35; i.e., SD of ln[PbB]=.30), an alpha value of 0.05 and a power of 0.95, and a minimum detectable difference of interest of 1.25 times, we estimated a sample size per group of 48 children, or 96 children per boatyard.

$$n_1 = \left(1 + \frac{1}{r}\right)\left(Z_{\alpha/2} + Z_{\beta}\right)^2 \frac{\sigma^2}{(\mu_2 - \mu_1)^2}$$

where μ_1 and μ_2 are the means of populations 1 and 2 respectively, σ is the standard deviation, r is equal to n_2/n_1, n_1 and n_2 are the required sample sizes from populations 1 and 2 respectively, Z is the standard normal deviate and α and β are the required type I and type II errors respectively.

It was hoped to obtain such a sample of children living in the vicinity of each of the three boatyards in the study area, i.e. 3*96=288 children. As some values were likely to be missing, and allowing for mis-estimations, a sample of 300 children was aimed for.

2.2.2 Child sampling method

Intended child sampling method

It was intended that children be recruited from the list of the National Housing Authority, Songkhla Office, which provided almost every house in the area. Households had been selected using a spatially random sampling from map provided by the Town Planning Office. House position would be linked subsequently with house number, and house number would be related afterward to child number. This sampling method, however, could not proceed because more than 80 percent of children could not be related with house number on the map.

Revised child sampling method

From a combined list of eligible children, random samples were drawn, stratified by village of residence, with the sampling fraction dependent on the sampling density by proximity of the village to a boatyard. High sampling density was performed in villages within 1 kilometre of a boatyard, in which a density of one child in 1080 m^2 meant having an average inter-child distance of 50 metres. Those living more distant were selected with a lower sampling density of one child in 4330 m^2 giving an average inter-child distance of 100 metres.

Table 2.1 Child samples stratified by village of residence.

Village	Estimated area (m^2)	No. of children in village	Sampling density (m^{-2})	Average inter-child distance (m)	No of children needed	No. of children obtained
1*	70,000	~200	1080	50	65	65
2	189,000	153	1080	50	175	153
3	73,000	233	1080	50	68	68
4	40,000	159	4330	100	9	9
5	48,000	111	4330	100	11	11
8	65,000	39	1080	50	60	39

* Only part of village 1 included.

2.3 Data collection

The data collection was divided into 3 parts: part 1 comprised determination of concentration of lead in children's blood, household dust and soil. Part 2 comprised an interview using a structured questionnaire regarding play behaviour, eating behaviour and other environment-contact behaviour, and the completion of an observation checklist. The last part was the recording of geographical information of household and soil sampling positions and boatyard positions.

2.3.1 Specimen collection and analysis.

Blood specimens

Blood specimens were collected on 9th, 12th and 13th February 2001 at schools by nursing staff of Singhanakhon Hospital. Venous blood specimens (approximately $4cm^3$) were taken from the cubital vein of each child, using lead-free disposable syringe and needle. A volume of approximately $3.5cm^3$ was stored sealed heparinized bottles at about 4°C. Three hundred and thirty blood specimens were collected, which included 30 specimens extra to the number planned, to allow for the loss of study data in the process of parent/guardian interviewing and/or loss of specimens during dust collection. The remainder of the blood specimen (about $0.5cm^3$) was used for haematocrit determination.

For quality control in lead contamination during children's blood collection processes, six specimens of de-ionized water were introduced via lead-free disposable syringe and needle similar to those used to collect blood specimens.

Total lead levels were measured at the Faculty of Tropical Medicine, Mahidol University, Bangkok, using a graphite furnace atomic absorption spectrophotometer (HITACHI Model Z-8200) with polarized Zeeman background correction, at a wavelength of 283.3 nm. The analytical detection limit of the analysis was 0.5 µg/dl. Calibration was made against Seronorm blood (Sero Corporation, Billingstad, Norway) as the reference material at reference values of 3.4 µg/dl (Lot 404107, analytical range, 3.1 - 3.9), 38.5 µg/dl (Lot MR9067y, analytical range 37.5 - 39.3) and 66.0 µg/dl (analytical range 61.1 - 68.7 µg/dl). Analytical values obtained for these references during analysis of the blood specimens for this study were 3.8 µg/dl, 39.6 µg/dl and 65.7 µg/dl, respectively.

Dust specimens

On 21st March 2001 to 11th April 2001, a home visit was made to the house of each child for interview of parent or guardians of each child and for household dust collection. Household dust specimens were obtained from a little disturbed area at a height of at least 1.5 meters above the floor of the main living area such as the top of door/window sills, ventilation holes or top of wardrobes. Dust was collected from at least 2 areas within the household by brushing lightly with a new toothbrush onto a clean paper sheet and then transferring the dust to new clear polyethylene bags until analysis. Two hundred and forty-six household dust specimens were collected. Total lead levels were measured by flame atomic absorption spectrophotometry at the Mining and Materials Engineering Department, Faculty of Engineering, Prince of Songkhla University.

Prior to analysis, the dust specimens were first dried at 80°C in covered, lead-free Petri dishes in an oven for 2 to 6 hours, then sieved through a 0.85mm nylon mesh to get rid of waste and again dried at 80°C for 2 hours. Portions of between 0.2 to 1 g were weighed and digested using concentrated nitric acid. Blanks were used for quality control of specimen digestion, undergoing the same treatment as the specimens. Lead concentration was determined using flame atomic absorption (FAA) spectrometer (GBC Model 905) at a wavelength of 283.3 nm. The analytical detection limit of the analysis was 10 mg/kg. Samples were digested in triplicate. Accuracy and precision of lead analyzed were checked by running lead content standards intercalated between every 10 samples.

Soil specimens

Soil specimens were collected in June 2001, from the top 2 centimeters located at the interstices of a square grid pattern (side length 70m) superimposed on a map of the study area. At each sampling point, approximately 0.5kg soil was obtained using new plastic spoon where bare soil was present. If bare soil was not present the sampling position was shifted to within 3 metres or grass and debris were removed. Specimens were stored in lead-free clear polyethylene bags until analysis. One hundred and fifty-seven soil specimens were collected in total. The specimens were transported to the Laboratory of Mining and Materials Engineering Department, Faculty of Engineering, Prince of Songkla University, Thailand.

The soil specimens were first dried for analysis at 80°C in an oven for 2 to 6 hours, then passed through a 0.85mm nylon mesh to remove grass, roots and other coarse particles and dried again at 80°C for 2 hours. Digestion and determination of lead concentration followed the same techniques as for the household dust specimens.

2.3.2 House condition and environment-contact behaviours

On an arranged day for each school, an interview was held with each child using a structured questionnaire to obtain information regarding the child's play behaviour, eating behaviour, and activities in and out of the home related to environment-contact. Three hundred and thirty school children were interviewed. The parent or guardian of each child was also interviewed during the home visits regarding the same behaviours and activities as in the child interview. At the home visit, observation checklists were used to record details of household condition and other potential lead contamination sources within or in the immediate surroundings of the household. Two hundred and forty six households were visited. Fourteen households could not be found in this process because of inaccurate school registration or house-moving. The remaining discrepancy between number of household included and the number of children was due to more than one child in the study residing in the same household.

2.3.3 Geographical variables collection.

A base map of the study area was supplied by the Songkhla Office of Public Works & Town, Country Planning in the format of MapInfo software, which was then transferred to the format of Surfer software.

Co-ordinates (XY) of sampling positions were plotted on the base map using Universal Transverse Mercator system (UTM) to reference each point.

Household dust sampling position.

The position of households in study area followed the information from the National Housing Authority, Songkhla Office, which provided the position of almost every house in the area, and these positions were incorporated with the base map. In addition, local health worker volunteers led the way to the households where information was unavailable. The positions of the households sampled were marked on the base map during the home visit.

Soil sampling position.

From the interstices of a grid pattern superimposed on the base map of the study area, the locations for soil sampling were determined by step counting and reference locations, such as road junction, mosque or school.

2.4 Exposure variables.

The exposure variables for childhood lead contamination were considered in 5 groups: bio-socio-demographic characteristics, household-condition, lead levels in soil and household dust, environmental child-contact behaviours and geographical variables, as below.

Table 2.2 Classification of exposure variables.

Variables	**Measurement**
Environmental lead levels	
- Household dust lead	mg/kg
- Soil lead	mg/kg
Bio-socio-demographic variables:	
- Age	Years
- Sex	Male/female
- Occupation of parents	7 categories
- Working related to repairing wooden boats of family members	2 categories
Geographic variables:	
- Household dust sampling position	XY co-ordinates (UTM)
- Soil sampling position	XY co-ordinates (UTM)
- Approximate location of schools and boatyards	XY co-ordinates (UTM)
- Distance between children's house and nearest boatyard.	Metres

Table 2.2 Classification of exposure variables (cont.)

Variables	**Measurement**
- Direction of nearest boatyard to children's house.	Continuous (degrees)
Household condition variables:	
- Type of floor	4 categories
- Type of wall	4 categories
- Eating place	4 categories
- Sleeping place	3 categories
Environmental-contact child behaviour variables:	
- Frequency of playing of various playing types	3 levels
- Frequency of playing in various places	Indefinite no. of categories
- Frequency of swimming in the lake	3 levels
- Frequency of going into boatyards	3 levels
- Frequency of ingestion of non-food items.	4 levels
- Frequency of playing with pet	3 levels
- Frequency of washing hand before eating	3 levels
- Activities in boatyards	3 categories
- Playing in the shoe-removal area*	2 categories

* The area in front of the house where shoes are removed before entering the house.

2.5 Plan of analysis

The data were computerized using EpiData 2.1 with double entry and cleaned and analyzed using Stata 7 statistical software. Geographical data were analyzed using Surfer 8 software[69] (Golden Software, Inc 2002) and statistical analysis performed using Stata 7.

Throughout the analysis, values of lead concentration of children's blood, household dust and soil were transformed to logarithms (base-2) because the distribution of lead levels were in all cases skewed to the right. Information regarding childhood behaviour obtained from the child interview and parents or guardians interview were compared. Subsequently, childhood behaviour data from parents or guardians was chosen because of low confidence in some information provided by the young age group.

To thoroughly understand the pattern of environmental and childhood contamination in the proximately of boatyard, data analysis was performed in stages as detailed in the following subsections. The results of analysis at each stage, as well as some further details of methodology, are presented in Chapters 3, 4 and 5.

2.5.1 Non-spatial description

Both non-spatial data and spatially referenced data were initially described without reference to location, and the results are presented in Chapter 3. In addition to a description of the study area, summary values of demographic characteristics and behaviour patterns of the children, particle size analysis of the plumbo-plumbic oxide used in for boat repair, and non-spatial distributions of lead levels in children's blood, and in household dust and soil are presented.

2.5.2 Environmental lead

The analysis of environmental lead comprised both spatial analysis and statistical modeling. The general methodology is given below and some further methodological details and the result of the analyses are presented in Chapter 4.

Spatial analysis

The spatial distribution of lead levels in soil and household dust was analyzed in the following stages.

First, as the study area was situated on a narrow strip of land, the levels of lead throughout the study area were displayed as if distributed along a one-dimensional coastal strip, in order to reveal the broad pattern of soil and household dust lead in relation to the location of the boatyards.

Then, a 2-dimensional analysis was undertaken using Surfer 8.0 software. The sampling positions of soil and dust were plotted on a map of the study area and coded according to the range of lead content. Their spatial inter-dependence was then explored by constructing observational variograms in Surfer 8.0 of each environmental compartment, both for restricted directions and also omni-directional, and using several different lag distances. The model variograms best fitting the observational data were then used as the basis of interpolation to construct contours of environmental lead throughout the study area.

The estimation of soil lead content at the position of each household.

In order to examine the relationship between household dust lead content and soil lead content, the expected value of soil lead at the position of each household was obtained from the square grid sampling frame used for soil sampling. This was done in two ways: a) by interpolation from the soil contour obtained by kriging, and b) by Voronoi tesselation. In the first method, increasingly fine contours of soil lead were plotted and overlaid on a map showing the household locations, until each household coincided with a soil lead contour line, whose value was then taken as an estimate of the soil lead content at the household. In the second method, soil lead level of each household was estimated as being equal to the index point of Voronoi polygons constructed around each soil sampling position. These polygons were constructed using the 3Plot software[69]. Estimated soil lead levels from these two methods were compared, and the correlation of each set of estimates with household dust lead examined.

Statistical modeling of environmental lead

In order to investigate the dependence of environmental lead level on distance and direction from each boatyard, linear regression modeling of the logarithmically transformed lead content was undertaken. To avoid the problem of the possible influence of more than one boatyard on any position within the study area, the analysis was confined to the distance and direction from the nearest boatyard, but with all boatyards incorporated into the model. In the case of soil lead, distance and direction from the nearest boatyard were the only variables included in the modeling, whereas for household dust lead a number of other variables pertaining to the household where each dust sample was taken were also included. Thus it was possible to explore, not only the effects of distance and direction from the nearest boatyard, but also the possible influencing effects of type of house construction, various aspects of house condition and occupation of household members in boat-repair work. The significance of each variable was tested using partial F tests, as performed by the post-estimation command *testparm* command in Stata.

2.5.3 Childhood blood lead

The analysis of children's blood lead levels is reported in Chapter 5. A general spatial description was first undertaken, using first the 1-dimensional approach and then a 2-dimensional plotting of the location of each child's home on a map of the study area, to compare with the corresponding plots of environmental lead.

Statistical modeling of children's blood lead was conducted with three sequential aims, with lead levels adjusted for age and sex through out the modeling process. The first aim was to reveal the crude dependence of children's blood lead on distance and direction from the nearest boatyard. Following this, distance and direction were disregarded while a model was constructed to account as fully as possible for variation in blood lead on the basis of soil and dust lead, environment-contact behaviours of the children, occupation of household members in boat-repair work and particular practices of these workers. Finally, any remaining effects of distance and direction from the nearest boatyard were explored after already accounting for the effects of the above variables. In this way the extent to which any influence of distance and direction from the nearest boatyard operated through the intermediary of soil and/or dust lead could be evaluated.

As with the modeling of environmental lead, the significance of each variable during the modeling process was tested using the post-estimation *testparm* command in Stata.

CHAPTER 3: Descriptive findings

The descriptive findings are presented in 4 parts: Part 1 describes general information of study area, demographic characteristic of study subjects and particle size distribution of Pb_3O_4. Part 2 presents the descriptive distribution of lead levels in children's blood, household dust and soil. Part 3 examines the distribution of childhood blood lead levels among the levels of various non-spatial variables. The descriptive information is evaluated in the last part.

3.1 General information

3.1.1 Study area

The study area is located in southern Thailand in Songkhla Province and is situated on the narrow strip of land on the north and west of the mouth of Songkhla Lagoon. A map of the study site and the study subjects' residences is shown in Figure 3.1, in which the positions of households are represented by different symbols for each village.

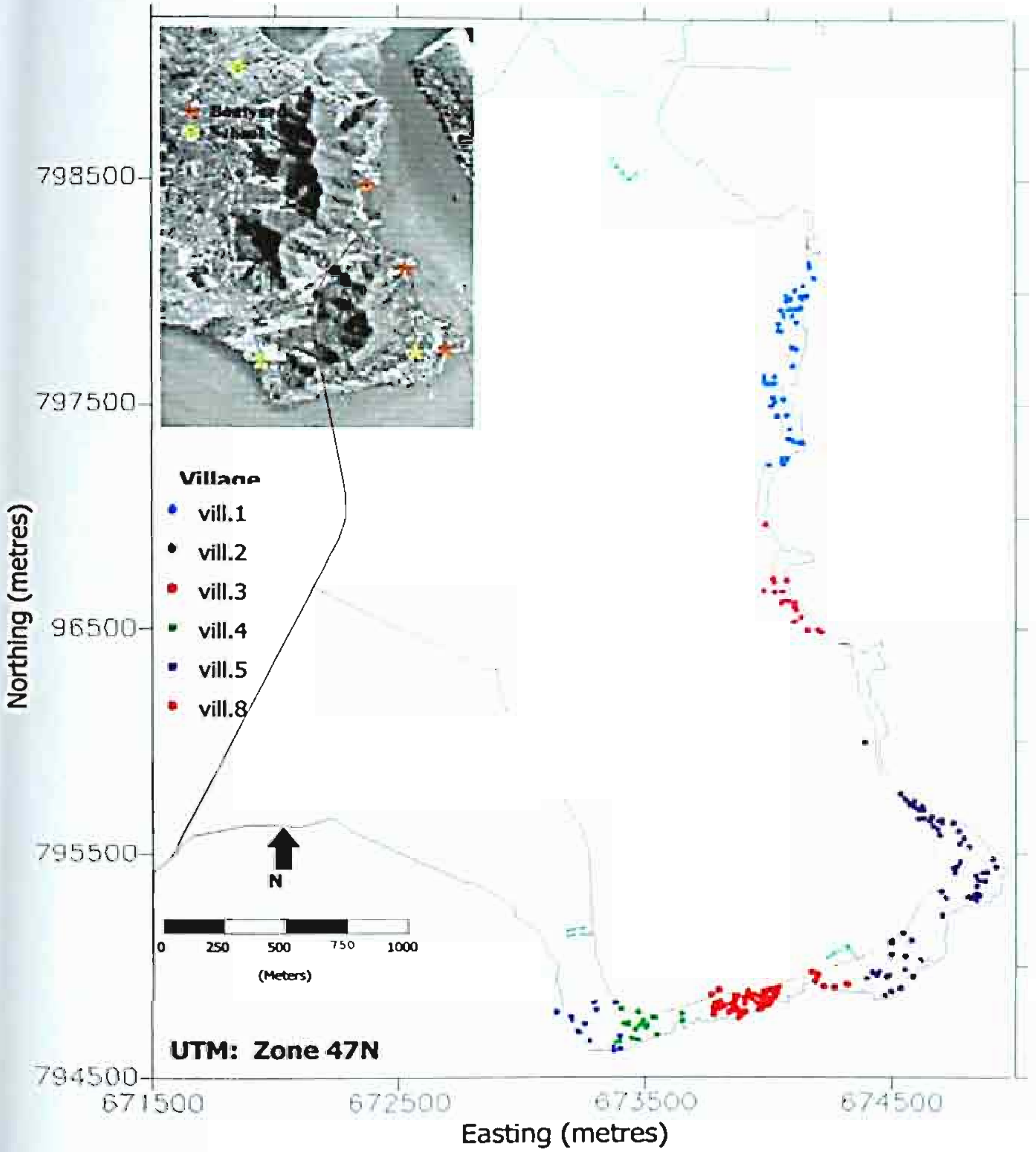


Figure 3.1 Map of the study area, the position of subjects' household in village 1, 2, 3, 4, 5 and 8.

3.1.2 Demographic characteristic of subjects

The distributions of sex, age and religion of the children are shown in Table 3.1. Approximately half of the study subjects were aged between 8 to 12, and there were slightly more girls than boys and Muslims than Buddhists.

Table 3.1 Sex, age and religion of children

	Frequency	Percentage
Sex		
Male	144	45.1
Female	175	54.9
Age group		
4.5 $\leq$ 6	25	7.8
> 6 - 8	53	16.6
> 8 - 10	85	26.7
>10 - 12	94	29.5
>12 - 14	62	19.4
Religion		
Buddhist	142	44.5
Muslim	177	55.5

Table 3.2 shows the current occupations of the children's parents. Fathers were mostly fishermen, labourers, merchants or boatyard workers; mothers were mostly merchants, housewives, labourers, office workers or fisherwomen.

Table 3.2 Current occupation of children's parents

	Frequency	Percentage
Father's occupation		
Fisherman	140	43.9
Labourer	68	21.3
Boatyard worker	41	12.9
Merchant	32	10.0
Office worker	6	1.9
Housekeeper	6	1.9
Others	26	8.1
Mother's occupation		
Merchant	108	33.9
Housewife	83	26.0
Labourer	41	12.9
Office worker	32	10.0
Fisherwoman	29	9.1
Boatyard worker	8	2.5
Others	18	5.6

Table 3.3 shows the distribution of household-condition variables. Approximately 57% of households were detached but the houses were very close to one another. The walls and floor of the majority of houses were made from concrete and wood. Members in more than eighty percent of the households slept on a mattress and ate on the floor.

Table 3.3 Children's household-condition characteristics.

Factors	**Frequency**	**Percentage**
Type of house		
- Detached house	183	57.4
- Row house	117	36.7
- Lifted floor house, rafted house	21	5.9
Type of floor		
- Concrete	160	50.2
- Wooden	139	43.6
- Linoleum	112	35.1
- Tile	47	14.7
Type of walls		
- Concrete	186	58.3
- Wooden	99	31.0
- Iron sheet	88	27.6
- Tile	12	3.8
Sleeping place		
- Mattress	267	83.7
- Bed	38	11.9
- Floor, mat	14	4.7
Eating place		
- Floor	256	80.2
- Table	41	12.9
- Make-shift bed	22	6.9

The environment-contact behaviour of children is shown in Table 3.4. About ten percent of the children reported sometimes or frequently eating food with their bare hands. Most of children (87.5%) never or almost never ingested non-food items. Sixty-five percent of them played in the shoe removal area in front of their house. Approximately 25% of children had gone into one of the boatyards at some time and 4.7 percent reported going into a boatyard more than once a week.

Table 3.4 Children's environmental-contact behaviours.

Contact behaviour	**Frequency**	**Children**
Washing hands before eating		
- > 1 time a week	116	36.5
- > 1 time a month to 1 time a week	119	37.4
- Never/≤ 1 time a month	83	26.1
Eating with bare hands		
- Never/≤ 1 time a month	289	90.9
- > 1 time a month to 1 time a week	18	5.7
- > 1 time a week	11	3.4
Ingestion of non-food items		
- Never/≤ 1 time a month	279	87.5
- > 1 time a month to 1 time a week	36	11.3
- > 1 time a week	4	1.2
Going into boatyards		
- Never /≤ 1 time a month	195	61.1
- > 1 time a month to 1 time a week	70	21.9
- > 1 time a week	54	16.9

Contact behaviour	Frequency	Children
Playing on the ground		
- Never/≤ 1 time a month	193	60.5
- > 1 time a month to 1 time a week	41	12.9
- > 1 time a week	85	26.6
Swimming in the lake		
- Never/≤ 1 time a month	114	35.7
- > 1 time a month to 1 time a week	46	14.4
- > 1 time a week	159	49.8
Playing on shoe off area		
- No	112	35.1
- Yes	207	64.9

3.1.3 The distribution of Pb_3O_4 particle size

Plumboplumbic oxide (Pb_3O_4) as used in boat repair was analyzed for size of particles using a Laser Particles Size Analyzer (COULTER LS230). Table 3.5 shows the range of distribution of particle size of Pb_3O_4 powder from eight replications. The overall range of the particle diameter was from 0.38μm to 76.42μm. Approximately 98% of the volume of the Pb_3O_4 powder had particle size between 2.01μm to 76.42μm. The range of mean particle size from eight replications was 17.33μm to 18.12μm.

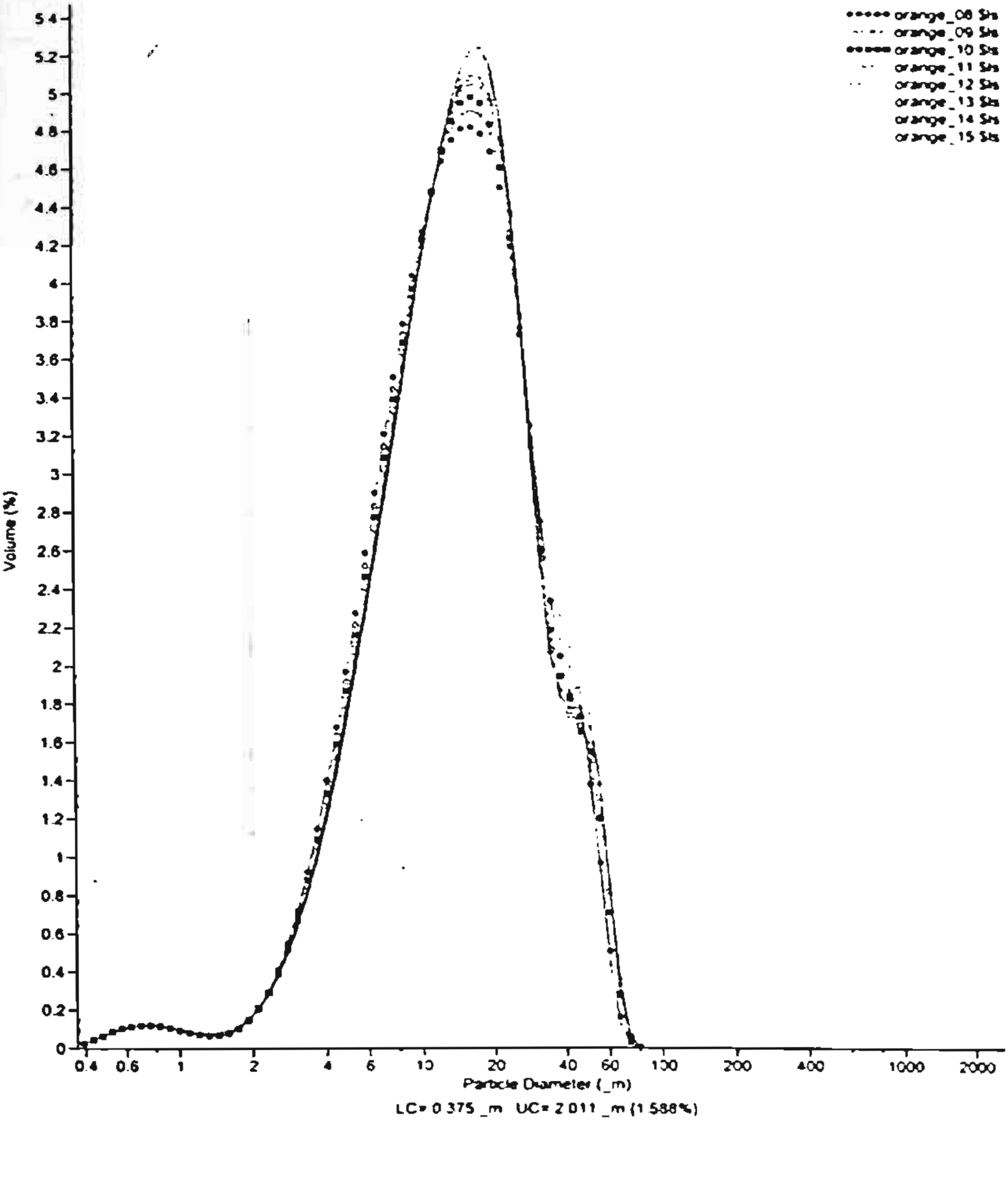


Figure 3.2 Frequency distribution of particle diameter of plumbo-plumbic oxide.

Table 3.5 The distribution of Pb_3O_4 particle diameter.

Pb_3O_4	Particle diameter	
	Peak 1 (0.38 to 2.01 μm)	Peak 2 (2.01 to 76.42μm)
Range of volume(%)	1.58-1.71	98.3-98.4
Range of mean(μm)	1.01-1.05	17.33-18.12
Range of S.D.(μm)	0.47-0.47	11.92-12.79

3.2 The non-spatial distribution of lead levels

3.2.1 Children's blood lead levels

The distribution of blood lead concentration of children is shown in Figure 3.3. The blood lead levels used in the analysis were not adjusted for haematocrit, as the reference levels are similarly unadjusted. The overall range of blood lead content was wide, 2 to 36 μg/dl. Geometric mean and standard deviation of PbB levels by age group and sex are shown in Table 3.6. Blood lead levels were slightly lower in girls than in boys and in both sexes generally decreased with age above 8 years, somewhat later in girls than in boys.

The Centers for Diseases Control, USA, (CDC) has defined the minimum level of concern for children's blood lead as 10 μg/dl, while the Public Health Ministry of Thailand defined the minimum level of concern for children's blood lead as 25 μg/dl.

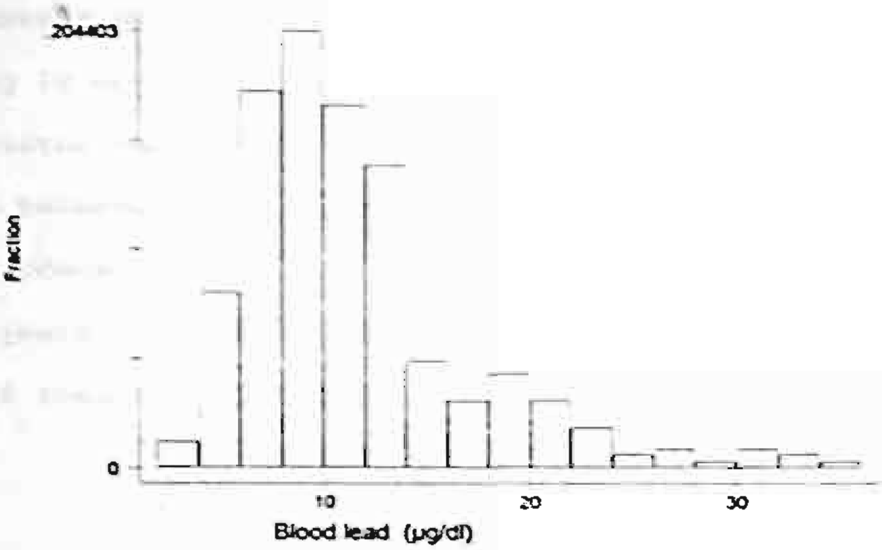


Figure 3.3 Distribution of children's blood lead concentration

Table 3.6 Children's blood lead concentration by age group.

Age	sex	Number of children	PbB (μg/dl)	
			Geometric mean	Geometric std dev
4.5 - < 6	Boy	12*	13.31	1.50
	Girl	12	10.71	1.37
> 6 - 8	Boy	30	13.33	1.59
	Girl	23	12.22	1.75
> 8 - 10	Boy	41	10.35	1.44
	Girl	44	10.73	1.54
>10 - 12	Boy	37	9.72	1.49
	Girl	57	8.49	1.58
>12 - 14	Boy	23	8.99	1.55
	Girl	39	7.38	1.59

* A blood specimen was not obtained from one boy in the age range 4.5 - 6 years.

Approximately 50 percent of subjects had PbB levels equal to or exceeding 10 µg/dl and 3 percent of subjects had PbB levels equal to or greater than 25 µg/dl (Table 3.7). Approximately, 75% of boy aged between 4.5 to 8 years had PbB exceeding the minimum level of concern (10 µg/dl). Moreover, 60% of girls aged between >6 to 8 years also had PbB above the level of concern and within this 4 of these 14 girls had PbB over 25 µg/dl.

Table 3.7 Percentage of children with blood lead concentration within various ranges specified by age group and sex.

Age	Sex	No of children	Percentage (number) of children		
			PbB <10 µg/dl	PbB 10-<25µg/dl	PbB ≥25 µg/dl
4.5 - < 6	Boy	12	25(3)	66.7(8)	8.3(1)
	Girl	12	50(6)	50(6)	0
> 6 - 8	Boy	30	23.3(7)	70(21)	6.7(2)
	Girl	23	39.1(9)	43.5(10)	17.4(4)
> 8 - 10	Boy	41	46.3(19)	53.7(22)	0
	Girl	44	34.1(15)	61.4(27)	4.5(2)
>10 - 12	Boy	37	54.1(20)	45.9(17)	0
	Girl	57	61.4(35)	36.8(21)	1.8(1)
>12 - 14	Boy	23	47.8(11)	52.2(12)	0
	Girl	39	66.7(26)	33.3(13)	0
Total		**318**	**47.5(151)**	**49.4(157)**	**3.1(10)**

* A blood specimen was not obtained from one boy in the age range 4.5 - 6 years.

3.2.2 Household dust lead levels

The distribution of household dust lead concentration is shown in Figure 3.4. The overall range of dust lead content is wide, 10 to 3,025 mg/kg. As the recommendation for concentration of concern for lead in dust is not available, the recommended level to protect children from intended ingestion of non-food items was used for the level of concern of lead in household dust, at the concentration of 150 mg/kg[70]. About 60 percent of households had dust lead levels equal to or exceeding 150 mg/kg and 20 percent of household had dust lead levels equal to or greater than 400 mg/kg (which the Ministry of Industry, Thailand, defined as polluted soil and needing treatment) (Table 3.8).

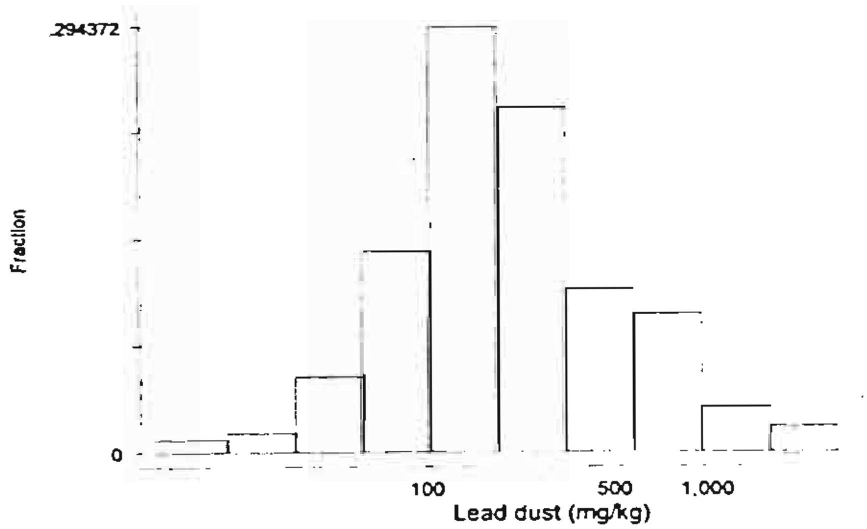


Figure 3.4 Distribution of household dust lead concentration (base-2-logarithm).

Table 3.8 Household dust lead concentration within various ranges.

Household dust lead (mg/kg)	No of specimens	Percentage of specimens
< 150	94	40.7
150 - <400	90	39.0
400 - <1,000	37	16.0
≥ 1,000	10	4.3

3.2.3 Soil lead levels

The distribution of soil lead concentration is shown in Figure 3.5. The overall range of soil lead content was very wide, 10 to 7,700 mg/kg. However, only 15% of soil specimens had lead levels above or equal to 150 mg/kg, although 9% of specimens had lead content equal to or more than 1,000 mg/kg (Table 3.9).

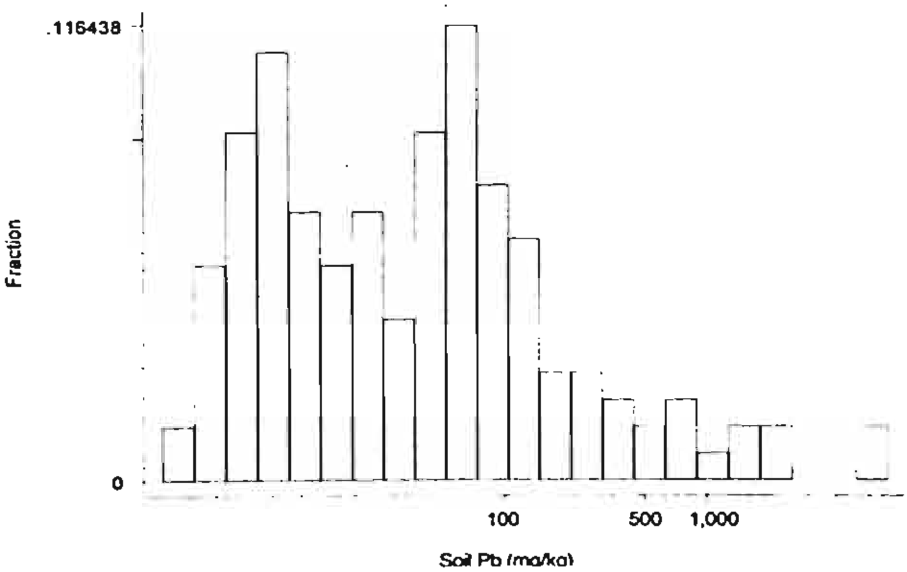


Figure 3.5 Distribution of soil lead concentration (base-2-logarithm).

Table 3.9 Soil lead concentration within various ranges.

Soil lead (mg/kg)	No of specimens	Percentage of specimen
< 150	134	85.3
150 - <400	9	5.7
400 - <1,000	7	4.5
≥ 1,000	7	4.5

3.3 Evaluation

In this chapter, the ranges of lead levels in children's blood, dust from household of each child's and soil from the area adjacent to boat-repair yards were reported. The geometric mean PbB of children in this study is high (at concentration of 9.91 µg/dl) compared to the mean lead level of general Thai children (at concentration of 5.55 µg/dl, analyzed at Institute of Pathology, Department of Medical Services, Thailand)[71]. Approximately 53% of children had PbB level exceeding the CDC minimum level of concern of 10 µg/dl, with a slightly greater proportion of boys (83 out of 143, 58%) than girls (84 out of 175, 48%)(P=0.074).

The concentrations of lead in soil and household dust have wide ranges. Considering the level of concern of lead in household dust and soil at 150 mg/kg, the majority (60%) of household dust had lead level exceeding or equal to this level, but only fifteen percent of soil specimens did so. Some specimens had very high lead content. Ten dust specimens (4.3%) and 7 soil specimens (4.5%) contained lead levels in excess of 1,000 mg/kg.

Thus, lead levels in all 3 compartments (2 environmental and children's blood) showed considerable variability. Questions then arise concerning the relationship of the lead levels in each compartment to the geography of the area, especially the spatial relationship with the boatyards and the level of inter-compartmental correlation, especially that between dust and soil lead. Moreover, the other factors influencing the levels of lead occurring in dust, soil and childhood blood in the vicinity of the boatyards need to be clarified. These issues form the substance of Chapters 4 and 5.

CHAPTER 4: Spatial distribution of environmental lead levels and their relationship.

The spatial distribution of lead is presented in 5 parts. The first covers the distribution of lead levels in dust and soil along the strip of occupied land along the coast of Songkhla Lake in the vicinity of the boatyards. The second part looks at the 2-dimensional distribution of lead in these two environmental compartments, and the third examines the relationship between the lead in the 2 compartments. The fourth part investigates the influence of distance and direction from the boatyards and of other factors on the levels of lead in the environment. Finally the understanding gained from these analyses regarding the spatial distribution of environmental lead in the vicinity of the boatyards is evaluated.

4.1 The distribution of environmental lead levels along the coastal strip - a 1-dimensional approach.

As the inhabited area in the region of the boatyards forms a narrow strip of land on northern and western part of the mouth of Songkhla lagoon, the distribution of households within the study area was initially explored in relation to positions along a "coastal strip" extending from village 5 at the southwestern end to village 1 at the northern end (Figure 4.1).

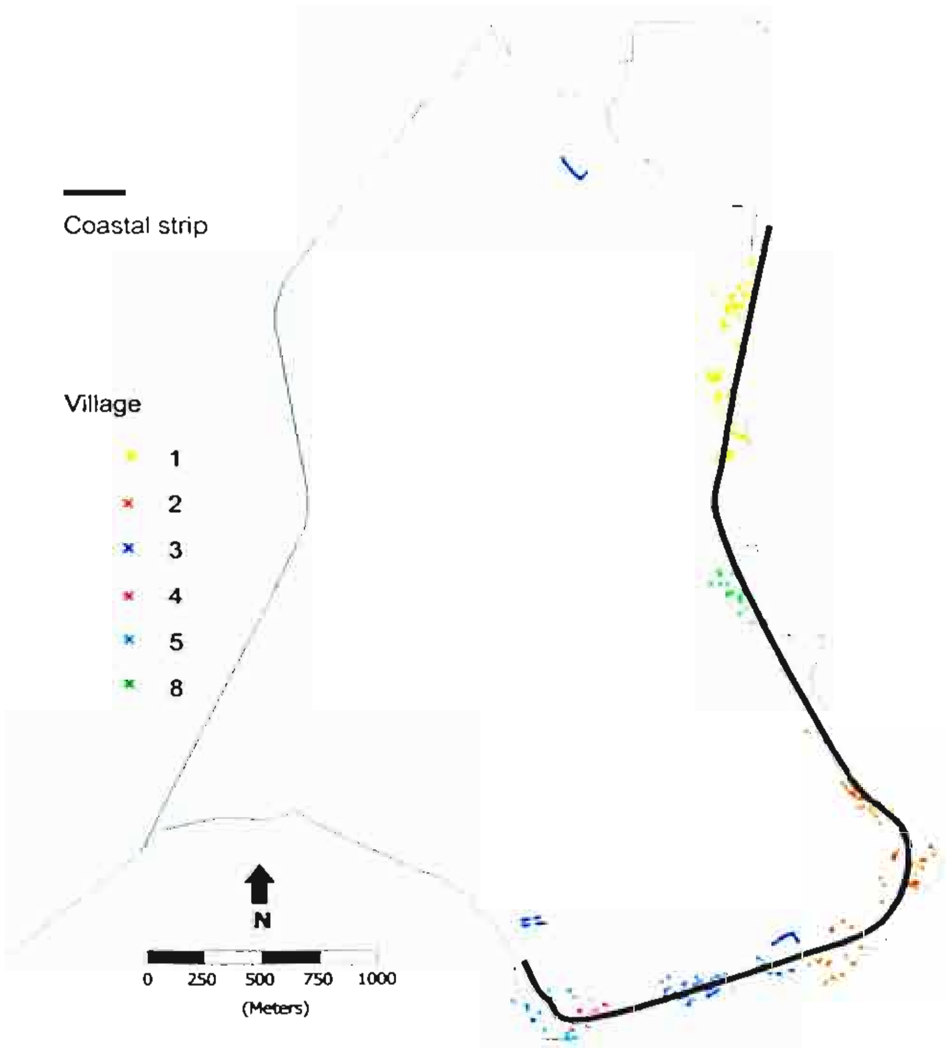


Figure 4.1 The coastal strip.

A line running approximately in the middle for the width of the occupied coastal strip of land in the study area was constructed on a map of the region (Figure 4.1) and the position of each household along the coastal strip taken as the point on the line at which a straight line from the household subtended perpendicularly. The village-8 end of the line was designated as position 0m and the line was almost 5 km long.

4.1.1 Household dust lead concentration.

The distribution of household dust lead levels along the coastal strip is shown in Figure 4.2. The X-axis represents the position of household along the coastal strip and the Y-axis the concentration of lead in household dust on a logarithmic scale. The vertical lines represent the position of the 3 large boatyards in the study area and the horizontal line at the concentration of 150 mg/kg marks the level of concern of household dust lead as used in this study. As a minimum level of concern for lead in dust is not available in the literature, the recommended maximum acceptable level of soil lead to protect children with a tendency or craving to eat substances other than normal food, 150 mg/kg, was used[70]. The majority of household dust specimens in this study had a lead level exceeding 150 mg/kg. The horizontal line at the concentration of 400 mg/kg shows the minimum level of soil lead that the Ministry of Industry, Thailand, has defined as "polluted soil". Twenty percent of the dust specimens in our study had lead levels exceeding this level. The distribution of dust lead levels shows evidence of peaks corresponding approximately to the location of each boatyard, but there is some evidence of high dust lead levels at distances from the boatyards.

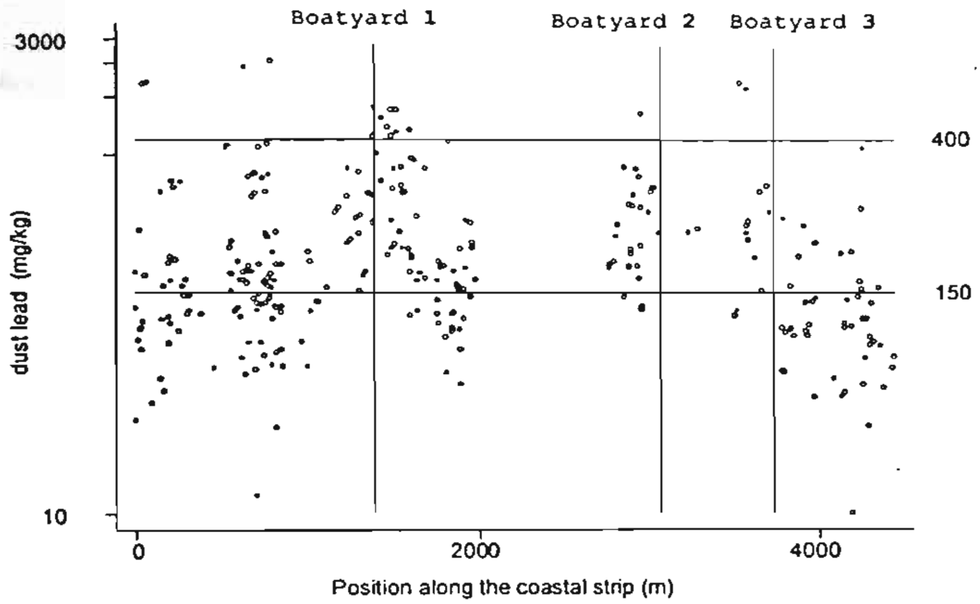


Figure 4.2 Distribution of household dust lead concentration along the coastal strip. Note the logarithmic y scale.

4.1.2 Soil lead concentration.

Figure 4.3 shows the distribution of soil lead along the coastal strip. The vertical and horizontal lines represent positions and levels as in Figure 4.2. The concentration of lead in most soil specimens is less than 150 mg/kg. However, there are some very high lead levels which perfectly correspond to the location of boatyards.

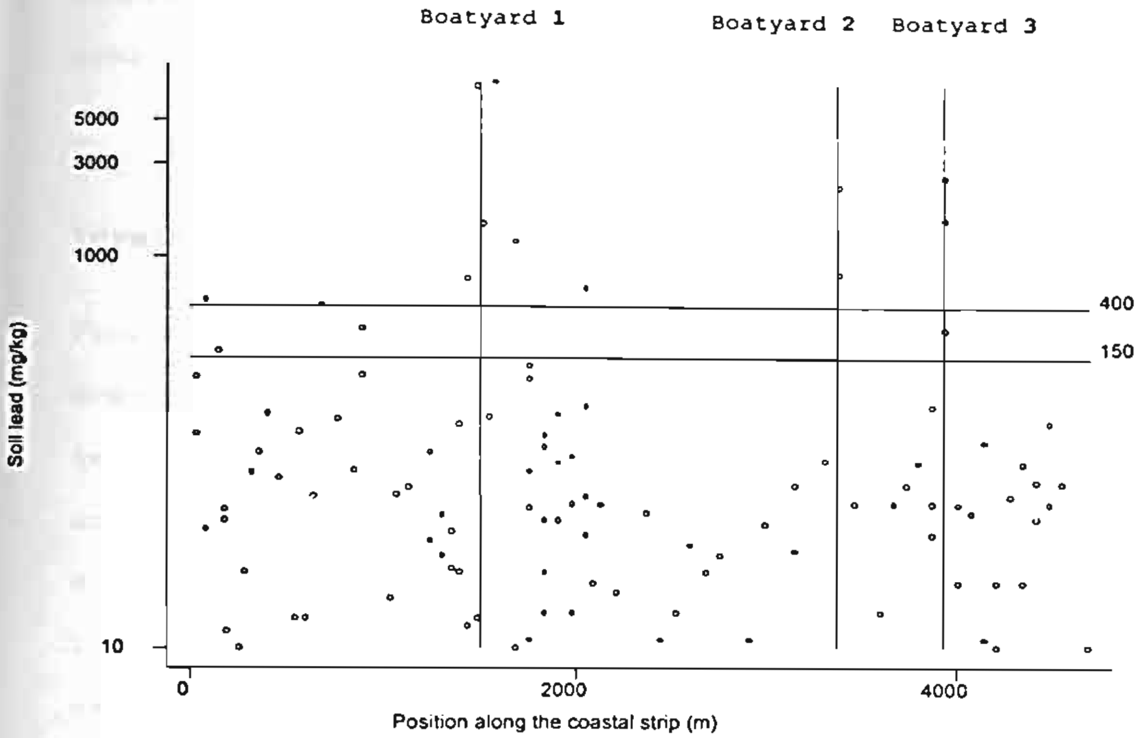


Figure 4.3 Distribution of soil lead concentration along the coastal strip. Note the logarithmic y scale.

4.2 The spatial distribution of lead concentration - a 2-dimensional approach.

The spatial distributions of lead contamination in household dust and soil are presented as a distribution map of the sample specimens of each type and as contour maps. For each distribution map, a classed post map of lead levels was superimposed on an aerial photograph, and categorized into 5 ranges at concentrations of 10-<150, 150-<300, 300-<500, 500-<1000 and $\geq$1,000 mg/kg, in order to display the magnitude of lead concentration in each sampling position. To create contour maps, a kriging method was used.

4.2.1 Two-dimensional distribution of household dust lead levels.

Figure 4.4 depicts the lead levels at each dust sampling position, ordered into 5 ranges. The distribution of high dust lead levels (equal to or exceeding 500 mg/kg) were relatively clustered in areas corresponding to large boatyards with a few others sparsely distributed. Nevertheless, there are households of low dust lead levels distributed throughout the study area, even within the areas of clustered high dust lead levels.

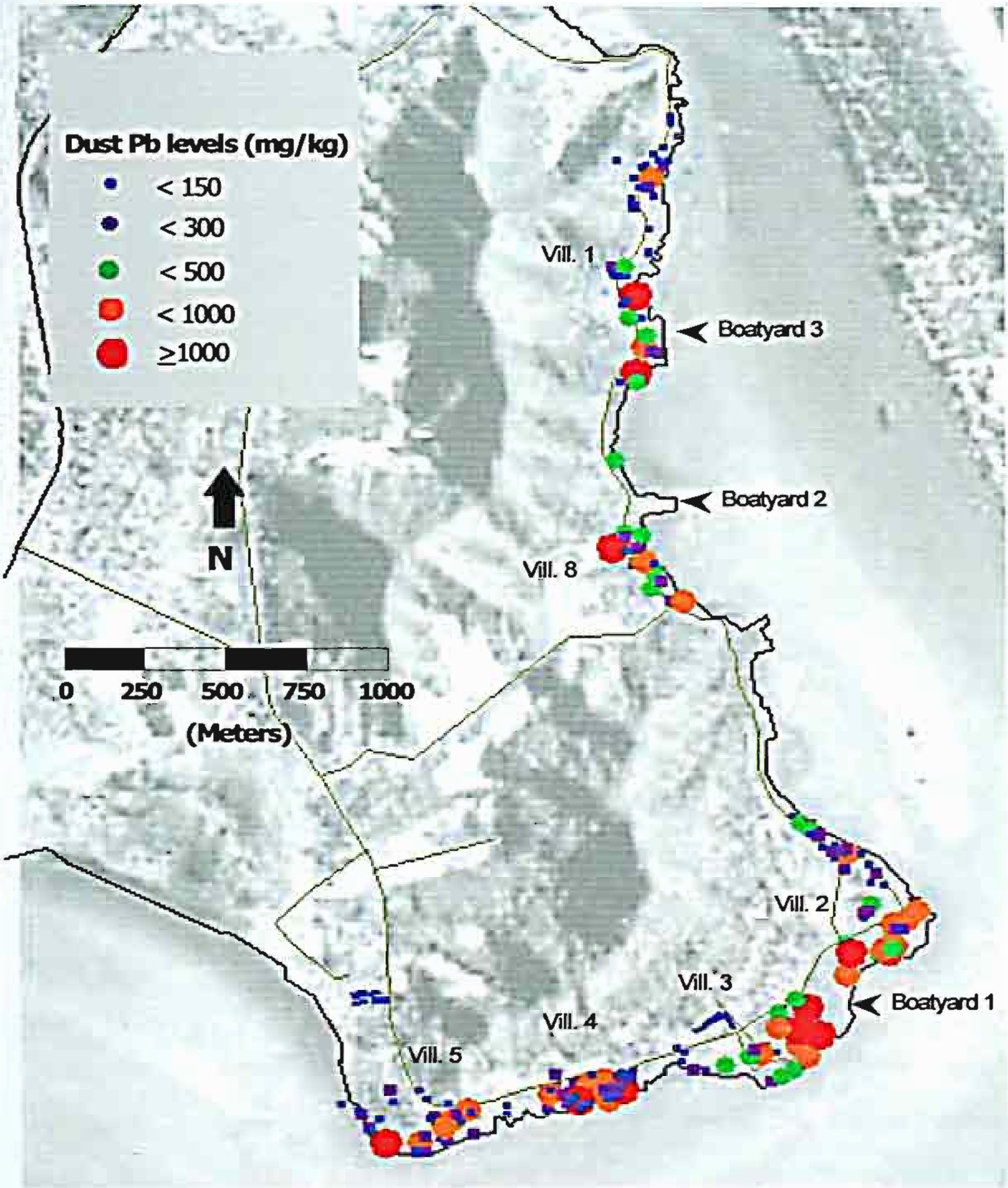


Figure 4.4 Spatial distribution of household dust lead levels superimposed on an aerial photograph of the study area.

However, the distribution map in Figure 4.4 imposes some limitation on the interpretation of the dust lead distribution pattern as the sampling positions were confined to the households of children enrolled in the study. To better appreciate the overall spatial patterns of household dust lead, contouring was undertaken. First, variograms based on logarithm (base-2) transformed observed data were constructed using Surfer software, version 8.0 (Golden Software Inc. 2002) and their dependency on direction explored. A suitable variogram model or models were fitted to the data and then used to construct contours of lead level covering the study area by the method of kriging. Kriging was used in preference to other methods of interpolation as it utilizes information from a larger number of surrounding data points.

The directional variograms were not greatly different and the omnidirectional variogram was therefore used. Figure 4.5 displays this variogram. The points marked as dots and connected by straight lines indicate the observational variogram of household dust lead, and the numbers are the numbers of pairs at each lag distance. The shape of the variogram is somewhat erratic and the variance at first lag is quite high. A linear variogram model with nugget effect was fitted using Surfer software, and is shown as the continuous straight line in Figure 4.5. The slope was equal to 0.00147 and nugget effect was 1.44. This variogram model was used for creating contours of household dust lead.

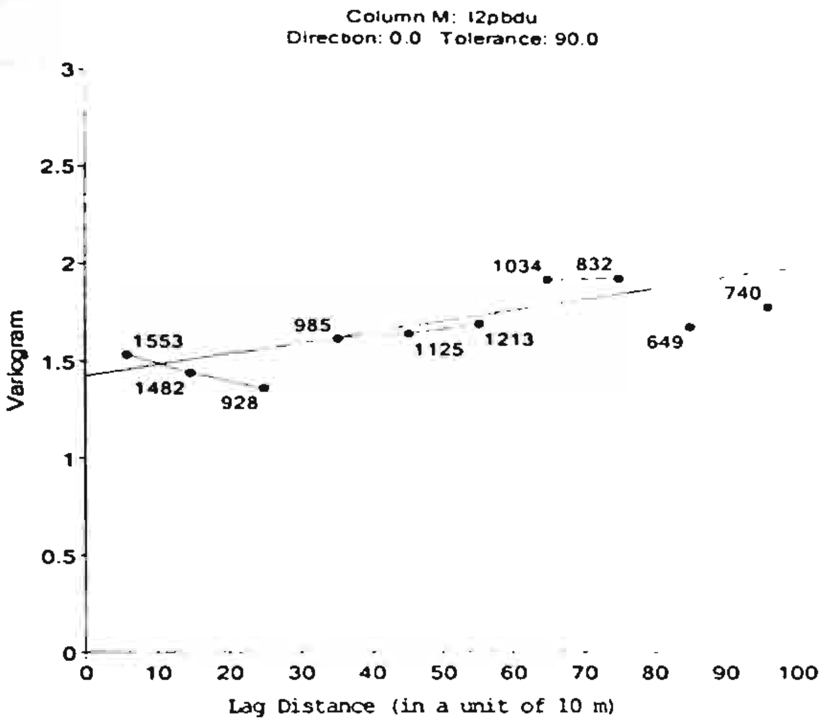


Figure 4.5 Omnidirectional variogram of household dust lead levels. (maximum lag distance 1300 m, lag width 100 m, nugget effect 1.493 and slope 0.00147).

The contours of dust lead (log-base-2 of dust lead in mg/kg), constructed using the above variogram model are shown in Figure 4.6. Spatial estimation over the study area was conducted by creating a square grid of 51 columns and 100 rows (approximately 35mx35m in each grid unit). Hot-spots are apparent, corresponding to the immediate surroundings of boatyard 1, in which the modelled concentration reaches a spot peak of about 1000 mg/kg (red). The concentration gradually decreases to 150 mg/kg to the west and also slowly decreases to 100 mg/kg to the north but with a small peak of approximately 250 mg/kg in the area of Village 8 . The concentration of lead in other areas is mainly within the range 180 mg/kg (mid yellow) to 240 mg/kg (dark yellow).

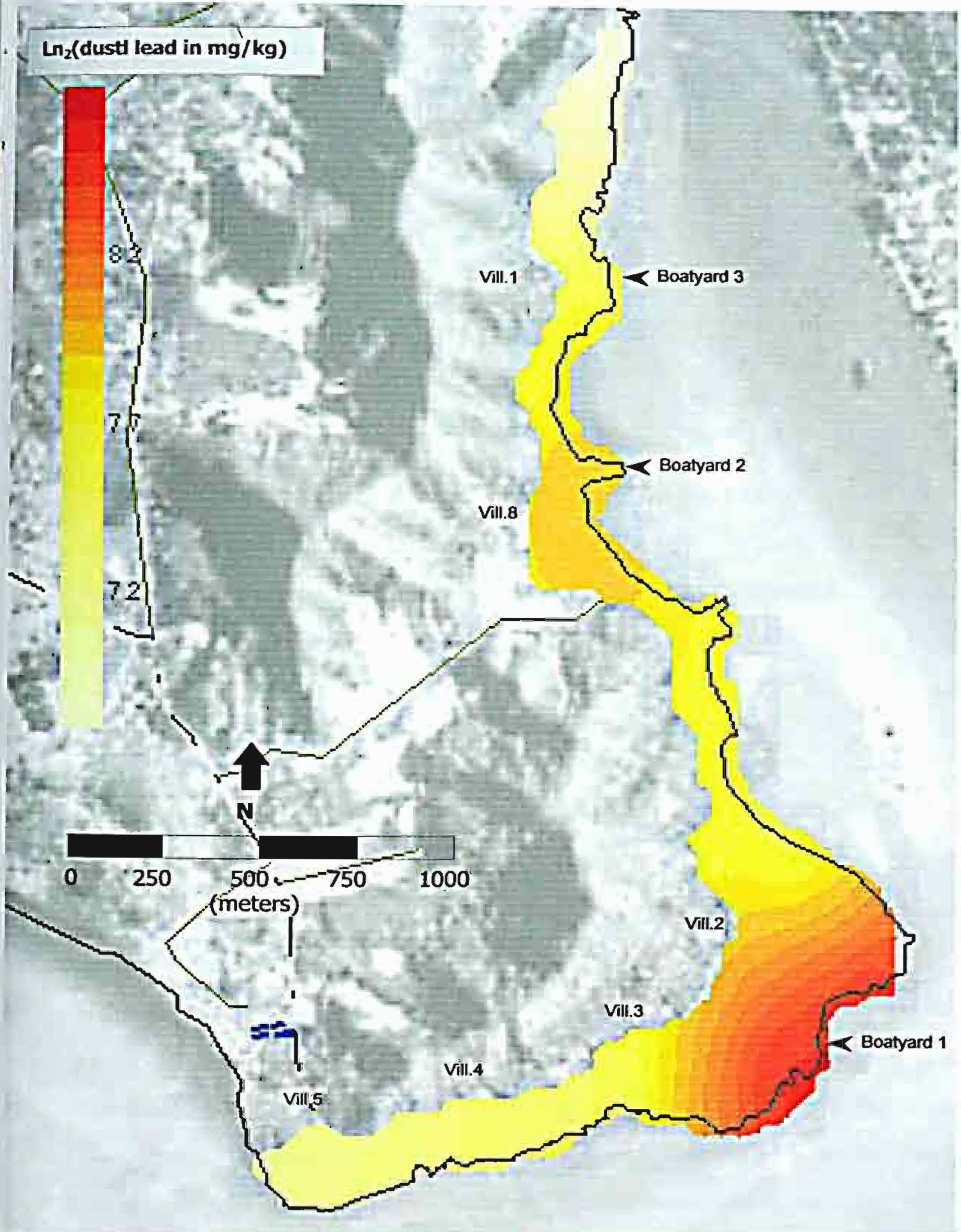


Figure 4.6 Contour map of household dust lead levels created using kriging.

4.2.2 Two-dimensional distribution of soil lead levels

The soil lead levels at each sampling point are shown in Figure 4.7. The concentrations of soil lead were mainly less than 150 mg/kg. The highest lead levels are clustered in the area closely related to the location of boatyards and rapidly decreased with increasing distance from the boatyards. However, there are lesser peaks in some area that do not correspond to the location of boatyards.

Nevertheless, the distribution map in Figure 4.7 shows only descriptive distribution of soil lead levels. Therefore, kriging method was applied to interpolate the spatial distribution of soil lead levels throughout the study area.

Figure 4.8 displays spatial variability of soil lead levels in all directions, as there was little evidence of directionality. Because the distributions of soil lead between upper and lower part of study area (separated at latitude UTM zone 47: 795759.78 North) were quite different, separate variograms were created for each part: Figure 4.8A presents the variograms of the lower part and Figure 4.8B the variogram of the upper part. The points marked by dots and connected with straight lines indicate the observational variogram of soil lead, and numbers are the numbers of pairs at each lag distance. The variogram of the lower part shows the variance reaching a plateau at a distance of 300m, whereas the variogram of the upper part shows little change in variation with increasing lag distance and there was not enough data to specify directional variograms. Omnidirection model variograms were therefore applied separately in upper and lower parts. Linear variogram models were fitted using Surfer software. Despite the plateau apparent in the variogram of the lower part, a linear model variogram fitted as well as a spherical model variogram, and was chosen as being the simpler of the two forms. The slope of the lower part was equal to 0.0418 and the nugget effect was 5.54. The slope of the upper part was 0.0029, with a nugget effect of 4.95. These variogram models are shown in Figure 4.8 as continuous straight lines and were used for creating contours of soil lead.

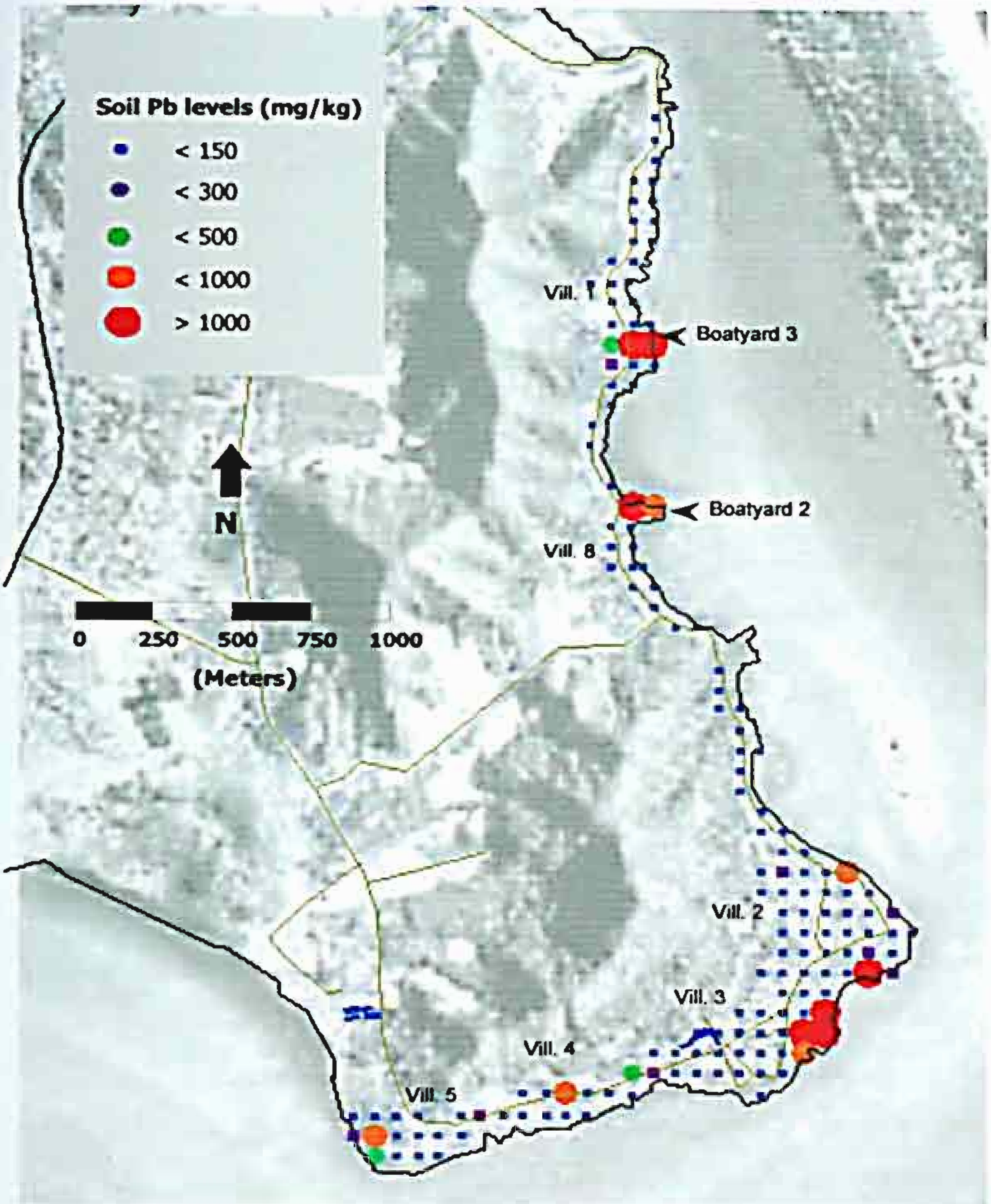


Figure 4.7 The distribution of soil lead at sampling points, superimposed on an aerial photograph of the study area.

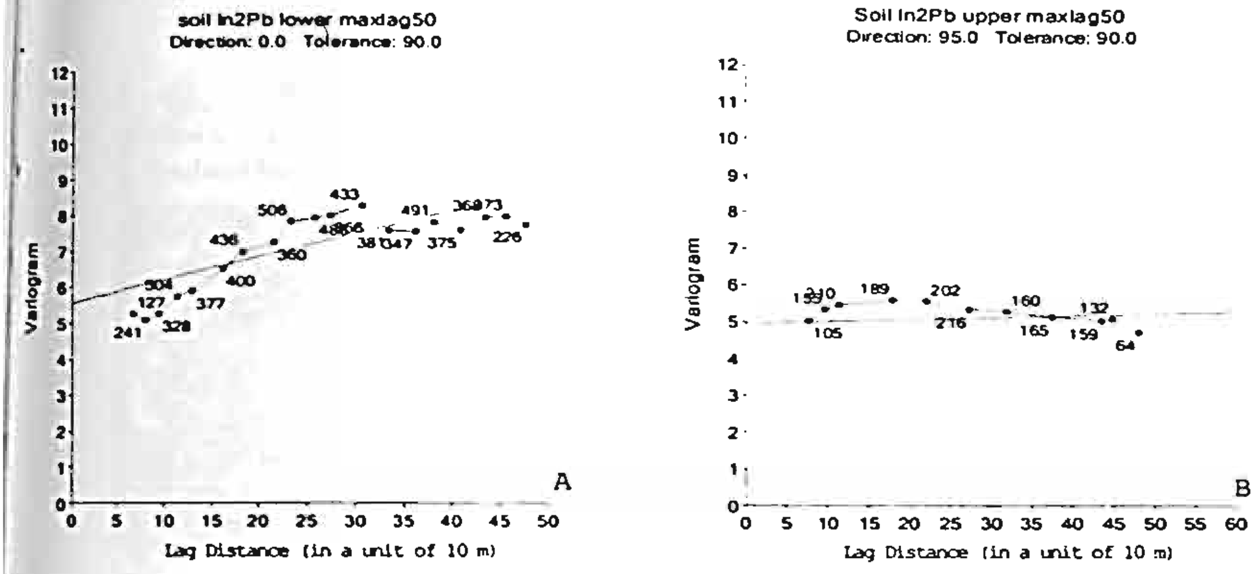


Figure 4.8 Omnidirectional variogram of soil lead levels. (A) Lower part of the study area (maximum lag distance 500 m, lag width 100 m, nugget effect 5.54 and slope 0.0418). (B) Upper part of the study area (maximum lag distance 500 m, lag width 100 m, nugget effect 4.95 and slope 0.0029).

The contour map of soil lead (log-base-2 of soil lead in mg/kg), constructed using the above variogram models is shown in Figure 4.9. The spatial estimation over lower part of study area was conducted using a square grid of 51 columns and 34 rows, while the upper part was constructed using a square grid of 18 columns and 69 rows (approximately 35m x 35m in each grid unit). Soil lead levels in the connecting area between two parts were used twice to fill the otherwise empty space. The differences in estimated soil lead level at this connecting area are very small, no greater than 5 mg/kg.

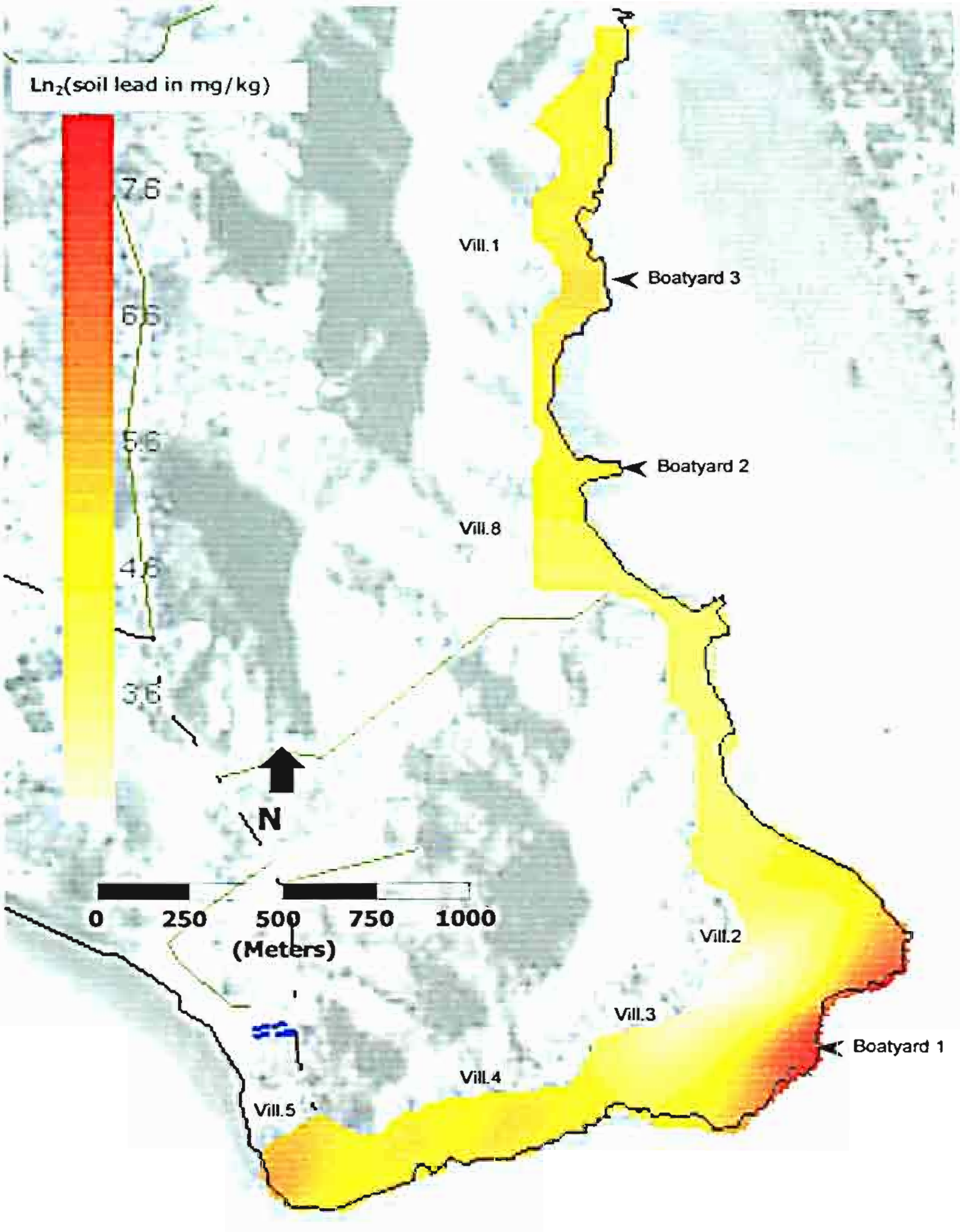


Figure 4.9 Contour lines of lead in soil created using kriging.

The distribution of soil lead levels interpolated by kriging method, ranged from about 10 mg/kg (pale yellow) to about 300 mg/kg (red). The distribution of soil lead shows a peak at the southeast part of the study area, where boatyard 1 is located. Soil lead levels rapidly decrease with increasing distance from the hot spot, then gradually increase again in both directions (to the west and to the north) but do not reach 100 mg/kg. Considering the level of concern of soil lead concentration to be 150 mg/kg (orange-red), there was only a relatively small area corresponding with the position of boatyard 1 which exceeded this level. However, the distribution of estimated soil lead levels throughout the study area did not exceed the minimum level of soil lead defined by Ministry of Industry, Thailand, of 400 mg/kg.

4.3 The spatial relationship between household dust lead and soil lead.

The estimation of soil lead concentration in each household position.

As the position of households, and therefore household dust specimens, did not correspond with soil sampling positions, a method to evaluate the relationship between dust and soil lead in the same position was required. Two approaches were employed: first, by the creation of a smoothed surface by interpolation among the soil sampling positions (contour map), and, second, by the use of Theissen polygons surrounding each soil sampling position - a technique known as tesselation.

Contouring method

A soil lead surface was created as described in section 4.2.2 and displayed as a contour map. The level of soil Pb at each household was then estimated using the residual of by Surfer software

To estimating the soil Pb level of each household, residual of soil contour were recorded which respected the household position. Household soil Pb were then calculated by transform log-base-2 of absolute residual because soil contour map was created in logarithm base-2 in unit of mg/kg . For example, the residual of household no.141 equal to 5.5. Thus, the soil lead content was taken to be $e^{(\ln 2 * 5.5)}$, that is, 45.2 mg/kg.

Tesselation method

Theissen polygons can be used to define areas of influence around each index point, in which every point inside the polygon is closer to the index point than to any other index point. They are constructed by drawing straight lines between adjacent index points forming a network of triangles, followed by placing perpendicular bisectors of each side of each triangle and extending them until they intersect with others. The polygons bordered by these bisectors are the Theissen polygons.

Figure 4.11 shows Theissen polygons of surface soil lead levels over the study area constructed using 3Plot Software[69]. The Theissen polygon map was transferred to Surfer software and a map of household positions overlaid. Thus, the lead content of soil at each household was estimated as being equal to the content of lead at the soil index point used to create the polygon in which the household fell.

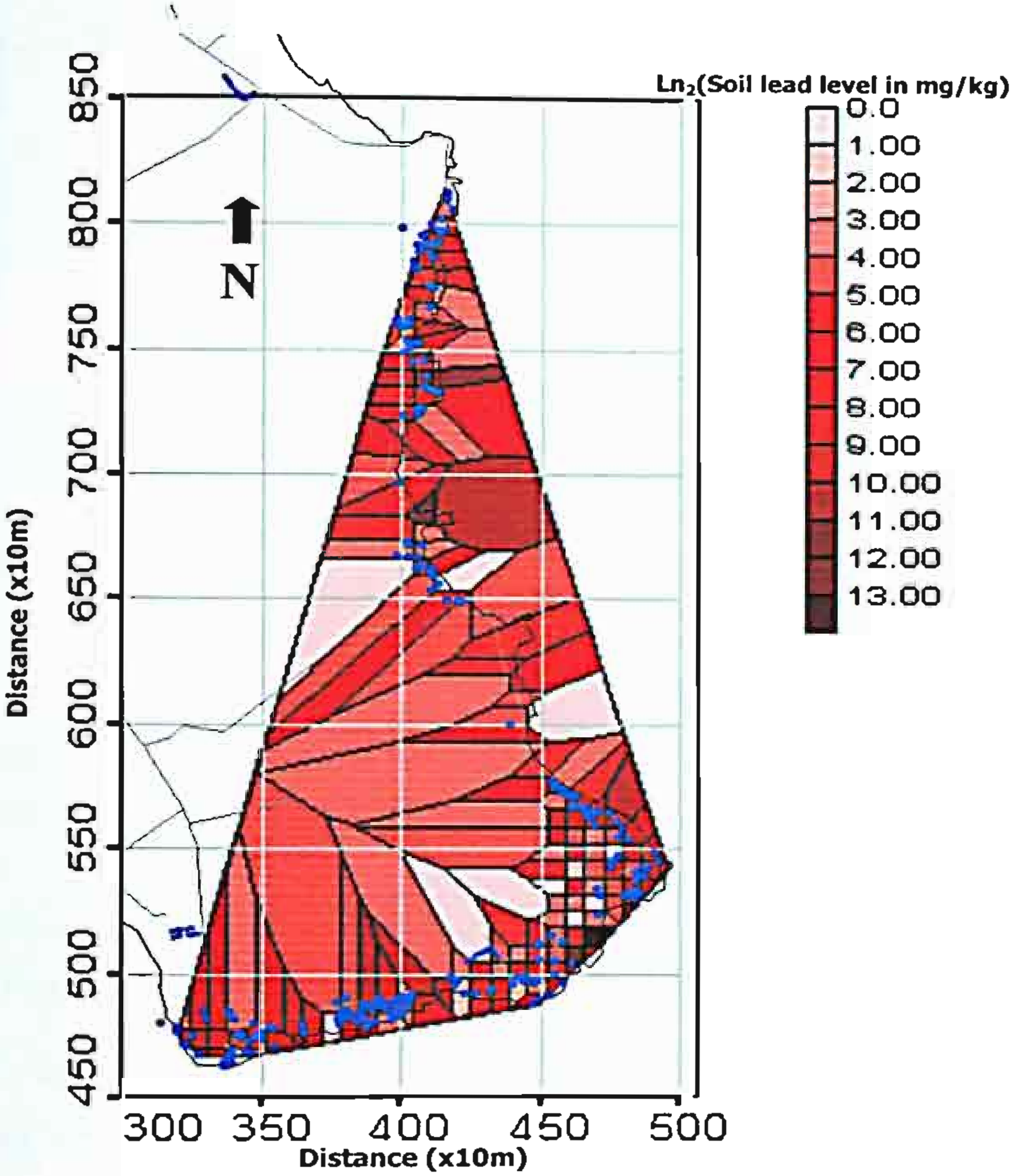


Figure 4.11 Thiessen polygons of soil lead level and position of households. The borders of the tessellated area are arbitrarily chosen to enclose the study area.

Figure 4.12 shows scatter plots of estimated soil lead on the x-axis against dust lead on the y-axis, both displayed as logarithm-base-2 of the lead content in mg/kg. Soil estimates are based on the contour method in Figure 4.7A and on the tessellation method in Figure 4.12B.

It can be observed that the distribution of estimated soil lead from contouring method covered a much narrower range than did that based on tessellation (13 to 137 mg/kg compared to 1 to 3895 mg/kg). This was the result mainly of the method used for construction of the soil lead (contoured) surface, which produced a somewhat smoothed surface that did not necessarily intersect exactly with the soil points used in its construction. Using the contouring method, there is a weak and not quite statistically significant correlation between soil and dust lead (Pearson correlation coefficient of 0.131) but there is no correlation evident when the soil values are estimated by tessellation (Pearson correlation coefficient 0.015) (Table 4.1).

In the subsequent analysis of how childhood blood levels might be influenced by the environmental lead levels at the positions of their household, the contour estimates of soil were used.

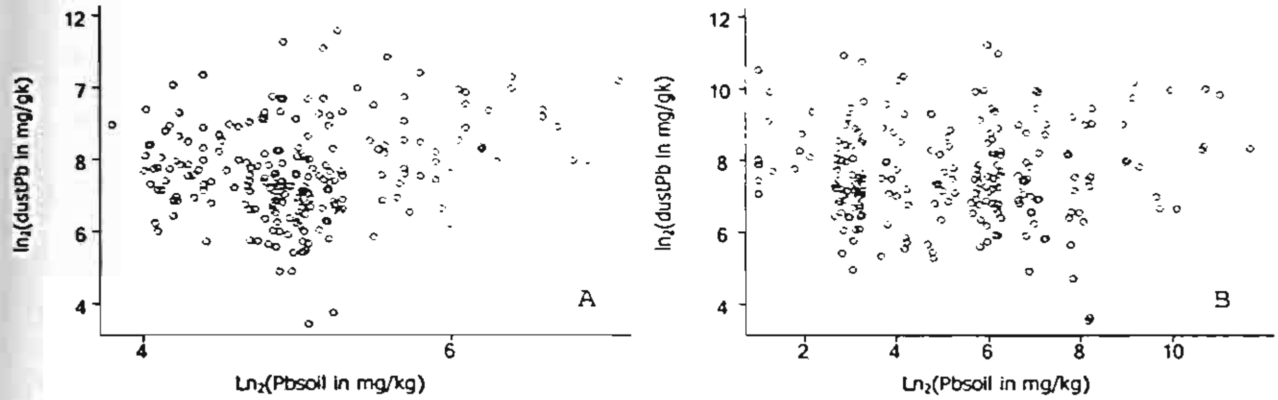


Figure 4.11 Scatter plots of dust vs soil lead levels in base-2 logarithm from 2 estimation methods: (A) Contouring and (B) Tessellation.

Table 4.1 Correlation of household dust lead levels and soil lead levels.

Soil lead estimated method	Correlation coefficient	P-value
Contouring	0.131	0.053
Tesselation	0.015	0.825

4.4 Factors influencing environmental lead levels.

Based on the assumption that the three boatyards in the study area were the primary sources of lead contamination, it was of interest to investigate the spatial relationship of environmental lead content according to distance and direction from each of these sources. As the variogram data for both soil and dust lead (as logarithmic values) were best explained by a linear model (with nugget effect), a reasonable approach to modeling the effects of distance and direction was to use linear regression on the logarithmically transformed soil and dust lead contents.

4.4.1 Spatial relationship of soil lead with respect to distance and direction from the boatyards.

On account of soil being sampled from the interstices of a square grid pattern of approximately 70m x 70m units throughout study area, and with no other position-referenced data, the influence of only distance and direction from the boatyards, and the interaction terms between boatyard and distance and direction, were sought. The directions from the nearest boatyard of each position were calculated by specifying the quadrant in which the position lay with respect to the boatyard. The defined quadrants were the area between directions from the boatyards to the northwest and northeast, the southeast and southwest, and the southwest and northwest. The quadrant between the direction northeast and southeast of the boatyards contained only two soil specimens and these were omitted from the analysis.

Table 4.2 Regression model of soil lead levels.

Factor	# of soil specimens	Coefficient	Multiplication factor	95% confidence interval	P-value
Boatyard (at source)					0.889
Boatyard 1	95	0	1		
Boatyard 2	19	0.0123	1.0085	0.330-3.080	
Boatyard 3	30	0.2571	1.1950	0.563-2.537	
Direction and distance from nearest boatyard (change with distance per 100m)					0.189
Northwest to Northeast	66	-0.1862	0.8789	0.761-1.015	
Southeast to Southwest	25	-0.2547	0.8381	0.646-1.087	
Southwest to northwest	53	-0.0173	0.9881	0.911-1.071	

<u>Note:</u> R^2 for model = 0.037

Coefficient of the model = 5.57

The model-estimated soil lead level at the position of the boatyard 1 was 47.66 mg/kg, 95%CI: 25.72 - 88.31 mg/kg.

Table 4.2 shows a linear regression model of soil lead levels in terms of the nearest boatyard and the distance and direction from the nearest boatyard. The coefficients for each term in the model have been re-transformed and expressed as multiplication factors for soil lead levels, ie, $e^{\beta \cdot \ln 2}$, where β is the coefficient. There were no significant differences in soil lead contamination among the 3 large boatyards, no significant trend in soil lead level with distance away from the nearest boatyard, and no significant differences among the three quadrants. Estimated mean soil lead concentrations at boatyards obtained from the model were low, in the range of 47.7 mg/kg to 56.96 mg/kg. Actual levels of lead in some soil specimens taken from the boatyards, however, exceeded 5,000 mg/kg. No significant interactions were found between boatyard and distance and direction. The model has a very poor fit to the data, explaining less than 4 percent of the variation in (logarithmically transformed) soil lead content.

4.4.2 Spatial and other factors influencing household dust lead levels.

The relationship of dust lead with distance and direction from the boatyards was also investigated. However, as the sampling positions were those of the households of children in the study, more information was available regarding the sampling points. Hence, it was possible to explore the effects not only of distance and direction from the boatyards, but also of the type of house, occupation of household members, and various household activities on the household dust levels.

Owing to the different spatial distributions of households around the boatyards, the directions were divided differently around boatyards 1 and boatyards 2 and 3. Around boatyard 1, households lying to the west of a straight line passing through the boatyard in a northwest-southeast direction were distinguished from the others, which lay mostly northeast of the line. Households lying closest to boatyard 2 or boatyard 3 were subdivided according to whether they lay to the north or to the south of the nearest boatyard. Distance and direction from boatyards 2 and 3 were not separated because of the small number of households and similar geographical factors surrounding these two boatyards.

Linear regression models were first constructed, as in the case of soil lead, by incorporating distance-direction from each of the main boatyards, and these terms were retained throughout the modeling process irrespective of their statistical significance. The resulting model was considered as the first-level model. Other variables were then included in the model and their statistical significance evaluated. These variables included occupation of household members in boat-repair work and various household conditions. Partial F-tests were performed on each variable and those significantly predicting the outcome ($P<0.05$) were retained while non-significant variables were removed. The resulting model was considered to be the second-level model.

This second-level model contained the nearest boatyard, distance-direction from the nearest boatyard, occupation of household members in boat-repair work and the cleanliness of house. Occupation of household members as a boat-repairer, either as a boatyard worker or as a small-boat (home-based) repair worker, was a significant predictor of dust lead. Among household conditions, only house cleanliness was marginally significant in predicting dust lead. The stages in the construction of this model are shown in Table 4.3.

Table 4.3 Successive stage in the construction of a model to explain household dust lead

	Model							
	I	II	III	IV	V	VI	VII	VIII
Boatyard	X	O	O	O	O	O	O	O
Distance-direction	X	X	X	X	X	X	X	X
Boatyard worker		X		X				X
Small-boat repair Worker			X	X				X
House cleanliness					X		X	X
Type of house						O	O	
R^2	0.205	0.239	0.230	0.259	0.223	0.221	0.237	0.276

X indicates a factor whose coefficient(s) jointly differ significantly from zero ($P < 0.05$).

O indicates a factor whose coefficient(s) do not differ significantly from zero.

Model I = first-level model; model III = second-level model.

Following construction of the second-level model, the various practices of the boat-repair workers, both those working in the large boatyards and those working at home, were examined for possible influences on household dust levels. The stages of modeling are shown in Table 4.4. Although the household dust lead levels were greatly elevated in homes of boat-repair workers (of either type), no significant differences in household dust lead levels could be identified among different practices of these boat-repair workers - for instance re-use of some materials such as paint containers from boatyards at home, use in the home of wood from old boats, keeping equipment and Pb_3O_4 at home, frequency of repairing boats in the home (Table 4.5).

Table 4.4 Addition of boat-repair worker practices to the second-stage model to explain household dust lead level (model VIII of Table 3). Adjustment has been made in all models for boatyard, distance/direction from the nearest boatyard, occupation in boat-repair work and house cleanliness.

Pratice variable	Model					
	IX	X	XI	XII	XIII	XIV
Boatyard worker practice						
Keep Pb_3O_4 at home	O					
Keep work clothes outside house		O				
Reused some material			O			
Boat-repair at home practice						
Frequency of working				O		
Keep Pb_3O_4 at home					O	
Keep equipment at home						O
R^2	0.278	0.276	0.282	0.281	0.277	0.277

O indicates a factor whose coefficient(s) do not differ significantly from zero ($P < 0.05$)..

Table 4.5 Effect of boat-repair workers' practices on household dust lead levels. Each practice is separately adjusted for distance-direction from the nearest boatyard and cleanliness of the house

Factor	No. of houses	Coeff-icient*	Multiplication factor	95% confidence interval	P-value
Boatyard worker					
Keeping Pb_3O_4 at home					0.447
- No	10	0	1		
- Yes	23	0.3478	1.273	0.682-2.373	
Keeping work clothes Outside the house					0.944
- No	19	0	1		
- Yes	14	0.0289	1.020	0.586-1.775	
Reused some material					0.214
- No	18	0	1		
- Yes	15	0.5450	1.459	0.803-2.652	
Boat-repair at home					
Frequency of working					0.265
- < 1 time a month	75	0	1		
- > 1 time a month	11	-0.4289	0.743	0.440-1.255	
Keeping Pb_3O_4 at home					0.558
- No	52	0	1		
- Yes	34	0.1451	1.106	0.768-1.593	
Keeping equipment at home					0.617
- No	47	0	1		
- Yes	39	0.1342	1.097	0.761-1.582	

The details of the second-level model (model VIII of Table 4.3 are shown in Table 4.6 and the residuals are plotted against fitted values in Figure 4.13. Variables significantly associated with household dust lead levels are distance-direction from nearest boatyard, occupation of family member and house cleanliness. The cleanliness of the house was scored by checking for the presence or absence of obviously evident cobwebs or deposits of dust in the frequently used areas, generally the living room, of each house.

As the dependent variable was logarithm (base-2) transformed, the coefficients for each term in the model have been re-transformed and expressed as multiplication factors for household dust lead in comparison with the reference categories. The re-transformation represents $e^{\beta \cdot \ln 2}$, where β is the coefficient.

Distance from the nearest boatyard significantly decreased dust lead levels in both directions from boatyard 1 and in direction to the north of boatyard 2 and 3. Household dust lead levels fell-off from boatyard 1 at a rate of about 6.7% per 100m (95%CI: 2.9%-10.4%) to the west and about 10.8% per 100m (95%CI: 3.1%-17.9%) to the northeast (calculated from $[1 - e^{-.1001 \cdot \ln 2}] * 100\%$, and $[1 - e^{-.1653 \cdot \ln 2}] * 100\%$, respectively). The levels fell-off at a rate of about 13.8% per 100m (95%CI: 4%-22.5%) to the north of boatyards 2 and 3 (calculated from $[1 - e^{-.2135 \cdot \ln 2}] * 100\%$). However, there was no statistically significant change in level of lead contamination in direction to the south of boatyards 2 and 3, probably because of the additional influence of the large boatyard number 1 to the south of boatyards 2 and 3. Also, the number of data points in this region was somewhat low and thus could not provide a reliable estimate of the change in household dust lead level with distance. Nevertheless, there were no statistically significant differences among the 4 directions in the change in household dust lead level with distance from the nearest boatyard.

The occupation of a household member in boat repair work, either in boatyards or at home, significantly increased lead levels, by 65.2% (95%CI: 18.4% - 130.5%, P=0.003) in households of boatyard workers, and 30.6% (95%CI: 4.8% - 62.6%, P=0.018) in households of small boat-repair workers.

The general state of cleanliness of the house also appeared to influence the level of dust lead. Those households classified in the survey as clean had a dust lead content about 21.9% lower (p=0.022) than households classified as dirty).

Table 4.6 Regression model of household dust lead levels.

Factor	# of dust specimens	Coefficient	Multiplication factor	95% confidence interval	P-value
Boatyard (at source)					0.390
Boatyard 1	162	0	1		
Boatyard 2	19	-0.6102	0.655	0.290-1.478	
Boatyard 3	50	-0.5460	0.685	0.393-1.193	
Direction and distance from nearest boatyard. (change with distance per 100m)					
Boatyard 1					0.003
West	110	-0.1001	0.933	0.896-0.971	
Northeast	52	-0.1653	0.892	0.821-0.969	
Boatyards 2, 3					
South	27	0.0759	1.054	0.763-1.457	0.006
North	42	-0.2135	0.862	0.775-0.960	
Occupation					
Boatyard worker in household /not	33/198	0.7242	1.652	1.184-2.305	0.003
Small boat repair at home/ not	86/145	0.3846	1.306	1.048-1.626	0.018
House cleaning					
Clean/dirty	125/106	-0.3570	0.781	0.632-0.964	0.022

Note: R^2 of optimized model = 0.276

Coefficient of the model = 8.43

The model-estimated household dust lead level at the position of the boatyard 1 was 345 mg/kg, 95%CI: 238.2 - 495.4 mg/kg.

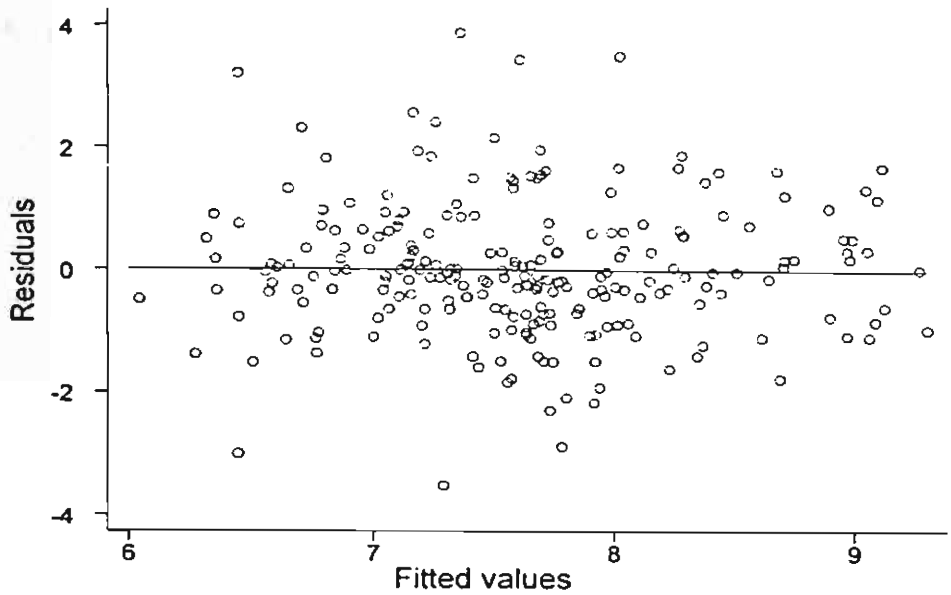


Figure 4.12 Residual plot of household dust lead model VIII.

Despite the identification of the influence of distance-direction from the nearest boatyard, occupation and house cleanliness on the levels of household dust lead, much of the variability in household dust lead level remains unexplained. The second-level model of household dust lead contamination could explain only about 28% of the variability in household dust lead content.

4.5 Evaluation

In this chapter, the spatial distribution of soil and household dust lead levels, their correlation, and factors influencing their distribution have been explored.

The distribution of household dust lead showed equally high peaks at various places within the study area, while the distribution of soil lead peaked most highly only at the location of boatyards. Thus the pattern of lead contamination in soil differed from that of contamination in household dust. Possible explanations are that dust specimens were sampled from low-disturbance positions, where dust probably represents the accumulated deposition of lead over some prolonged period, whereas soil specimens were obtained from open areas where the top-soil may readily have been disturbed by such factors as wind, leaching and run-off following rain or, in some places, high tides, or mechanical disturbance from vehicle, animal or human activity etc. Furthermore, owing to logistic reasons, the soil specimens were taken between 8 and 11 weeks after the household dust samples, during which time changes in the soil lead distribution could have occurred. Nevertheless, there was still a weak relationship between household dust lead and the estimated level of lead in the soil at the position of each house, as determined by the contour method, which agrees with results achieved by Murgueytio (1998)[4]. However, the spatial distribution of lead concentration in both soil and household dust displayed high spatial variability over a short distance, which was reflected in the high nugget effect in the variograms, especially in those for soil lead. The possible explanations for this short-distance spatially erratic distribution of soil lead could be related to the disturbances referred to above. The magnitude of this short-distance variation seems to be much too great to be explained by measurement error.

Distance-direction from the nearest boatyard was insufficient to explain the spatial pattern of soil lead content. It is likely that short-range factors exert much greater influence on the content of lead in the soil than does the spatial relationship to any of the boatyards. Because of the sampling design for soil lead, human activity variables could not be linked to soil sampling points, and data on site-specific environmental variables, such as vegetation cover, surface water flow, degree of mechanical disturbance etc, were not collected. Nevertheless, the lack of any clear relationship between soil lead and distance-direction from the nearest boatyard contrasts markedly with the corresponding relationship for household dust lead, which, even disregarding human influencing factors (occupation of household members in boat-repair work and house cleanliness) was quite unambiguous, explaining over 20 percent of the variation in lead content (Model I, Table 4.3).

An aspect of soil lead measurement which could have obscured the true distribution of soil lead is the determination of soil lead content on the basis of per unit dry weight of soil. This has the disadvantage in estimating the distribution of soil lead contamination from an external source as the estimated lead content is influenced by the differences in the density of the matrix, which might be quite variable among different 'soil' specimens. Thus, the estimated soil lead content (per unit weight) would overestimate the relative amount of lead deposited (per unit area) in specimens of low density compared with that in high density specimens. This is especially relevant to the 'soil' collected from the boatyards themselves, as this 'soil' contained large quantities of sawdust, and therefore was of low density.

Factors influencing household dust lead contamination included distance-direction from the nearest boatyard, occupation of household members in boat-repair work and house cleanliness. The change in dust lead content with increasing distance from a boatyard ranged from no evident fall-off (to the south of boatyards 2 and 3) to about 14 percent fall-off per 100 metres distance (to the north of boatyards 2 and 3). Superimposed upon this distribution, however, were local peaks associated with boat-repair workers' residences. According to the model, even in the direction in which the fall-off was maximal, the mean dust lead content in households of average cleanliness with no boatyard worker and no small boat-repair work remained above 150 mg/kg, which we may take as the maximum acceptable household dust lead level, for up to about 1005 metres to the west of boatyard 1, 610 metres to the northeast of boatyard 1, and about 215 metres to the north of boatyard 3.

More importantly, however, a "safe" distance from a boatyard should not be where only the mean dust lead is below the acceptable limit, but where the majority (say 95 percent) of households have a dust lead level (PbD) below the acceptable level. To obtain a rough estimate this safe distance, the standard deviations of $\log_2$(PbD in mg/kg) within 100-metre bands around each boatyard in households that did not have a boat-repair worker were calculated, and mostly were found to be equal to about 1.1. Thus it can be expected that 95 percent of households with no boat-worker would have levels of $\log_2$(PbD in mg/kg) below about mean + (1.64 * 1.1), or equivalently in untransformed units, 3.5 * mean PbD. If we accept some extrapolation beyond the collected data, this would place the safe distances for a household (of average cleanliness and with no boat-repair worker) from boatyard 1 at 2800 m to the west and 1700 m to the northeast, and about 1060 m to the north of boatyard 3. In fact, locating houses at such distances and directions from boatyard 1 would not be possible, as these positions are actually located in the lake itself. However, if the rates of fall-off of dust lead level found in this study are typical for areas surrounding boat-repair yards, then these distances should be taken into consideration when establishing new boat-repair yards or when settling communities in a boat-repair region. At the very least, communities living within such distances of a boat-repair yard should be recognized as being likely to have higher than acceptable dust lead levels, and appropriate advice and/or intervention provided.

The failure to find any significant differences in the rate of fall-off of household dust lead with distance in different directions around the boatyards was somewhat unexpected. It was assumed that the spread of lead in dust would be mainly by wind action. With the monsoon winds blowing predominantly from the northeast from mid-October to mid-February and from the southwest from May to mid-October, the spread of lead oxide dust from the boatyards was expected to be more extensive in those directions. It may be, however, that local wind eddies created by the adjacent hills and local buildings disturb the larger scale wind patterns.

Boatyard workers may play an important role in increasing household dust lead, probably by bringing home lead dust on their clothing, skin, hair, shoes, vehicle, etc. In some cases, boat-repair workers were found to keep their equipment as well as plumboplumbic oxide powder at home, which would seem to pose an additional risk of contamination. Our data, however, failed to reveal any significant difference in contamination burden associated with the variation in the practices of boatyard workers. Nevertheless, our finding of increased dust lead levels in households of workers exposed occupationally to lead is consistent with other studies among occupations involving lead[41;72;73]. In none of those other studies, however, was the source of lead the same as in the current study.

Despite the identification of several highly significant factors related to household dust distribution, our regression model could account for only 28 percent of the variation in household dust levels. Thus, there must be other, as yet unidentified, sources of variation. Non-systematic observations in the study area suggest that activities involving lead fishing net sinkers and old lead-acid batteries in household might add to the total lead contamination levels.

In several other studies, household dust lead levels have been shown to be a significant contributor to childhood lead contamination[74-76]. In the following chapter, therefore, which presents the investigation of children's blood lead levels, interest is focused on the relationship of household dust lead levels to childhood blood lead levels.

Chapter 5: Blood lead levels of children living in the environs of boat-repair yards, and contributing factors.

In this chapter, the results of the spatial distribution of children's blood lead levels and the identification of factors influencing the exposure of lead in children are presented. The spatial distribution of children's blood lead is described in both 1-dimensional and 2-dimensional formats. Factors contributing to childhood blood lead are explored more or less sequentially among basic biological variables (age and sex), environmental lead levels and environment-contact behaviour of children, and boat-repair occupation of household members and their various practices.

The effects of distance/direction from the boatyards are explored both at an early stage, i.e., adjusting only for age and sex, and at the end of the sequence outlined above, with the purpose of detecting spatial effects remaining after accounting for more immediate determinants of childhood blood lead.

An evaluation of the relationships is presented in the final section of the chapter.

5.1 The spatial distribution of children's blood lead concentration according to place of residence

5.1.1 The distribution along coastal strip (1-dimensional)

Figure 5.1 shows the distribution of blood lead along the coastal strip, which was defined in Figure 4.1. The X-axis represents the position of each child's residence along the coastal strip and the Y-axis the concentration of lead in each child. The vertical lines represent the position of the 3 large boatyards in the study area and the horizontal lines at the concentration of 10 µg/dl and 25 µg/dl mark the minimum level of concern of childhood blood lead of the Centers for Disease Control, USA, and that of the Ministry of Public Health, Thailand, respectively. Approximately fifty percent of children had lead levels in excess of the level of concern of 10 µg/dl, and there is some evidence of increased levels of PbB in children close to each boatyard. However, this graph also shows some evidence of peaks at a distance away from the boatyards. The peaks closely match those of household dust lead displayed in Figure 4.2.

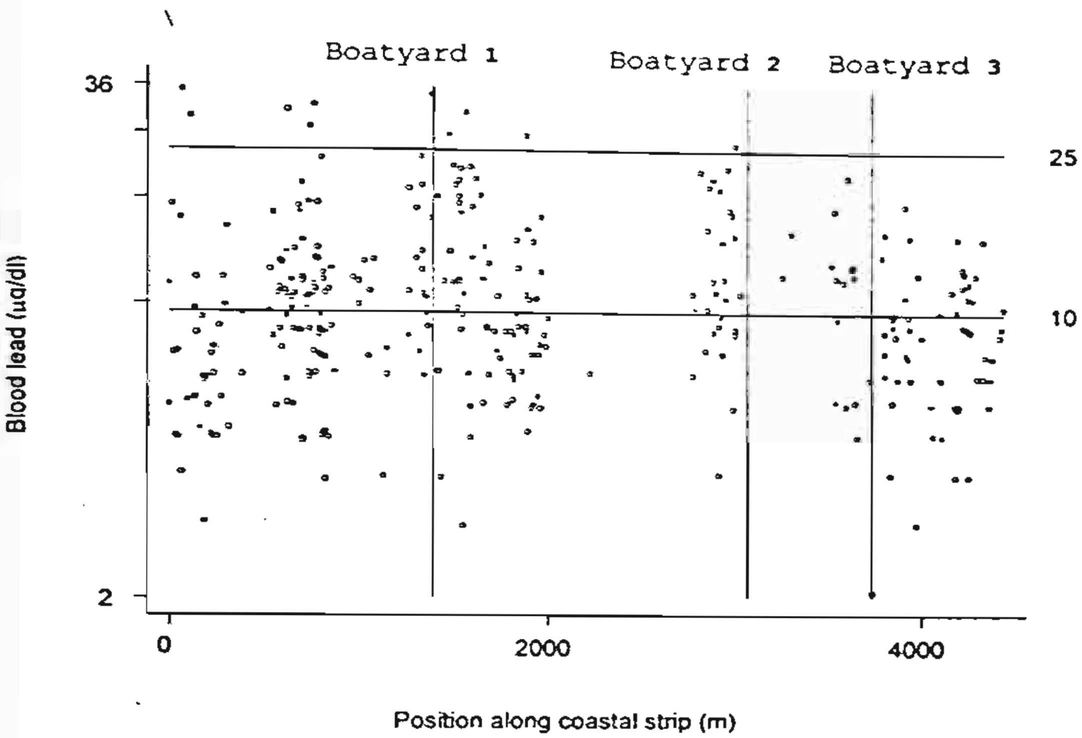


Figure 5.1 Distribution of children's blood lead concentration along coastal strip

5.1.2 The 2-dimensional distribution

Figure 5.2 shows the descriptive spatial distribution of children's blood lead according to the position of their residence divided into 3 ranges: ≥3 to <10 µg/dl, ≥10 to <25 µg/dl and ≥25 µg/dl. Children with the PbB level equal to or exceeding 10 and 25 µg/dl were living throughout study area. Moreover, there were high proportions of children with PbB concentration in excess of 10 µg/dl in some areas. Nevertheless, children with low PbB levels were also living close to children with high PbB concentrations.

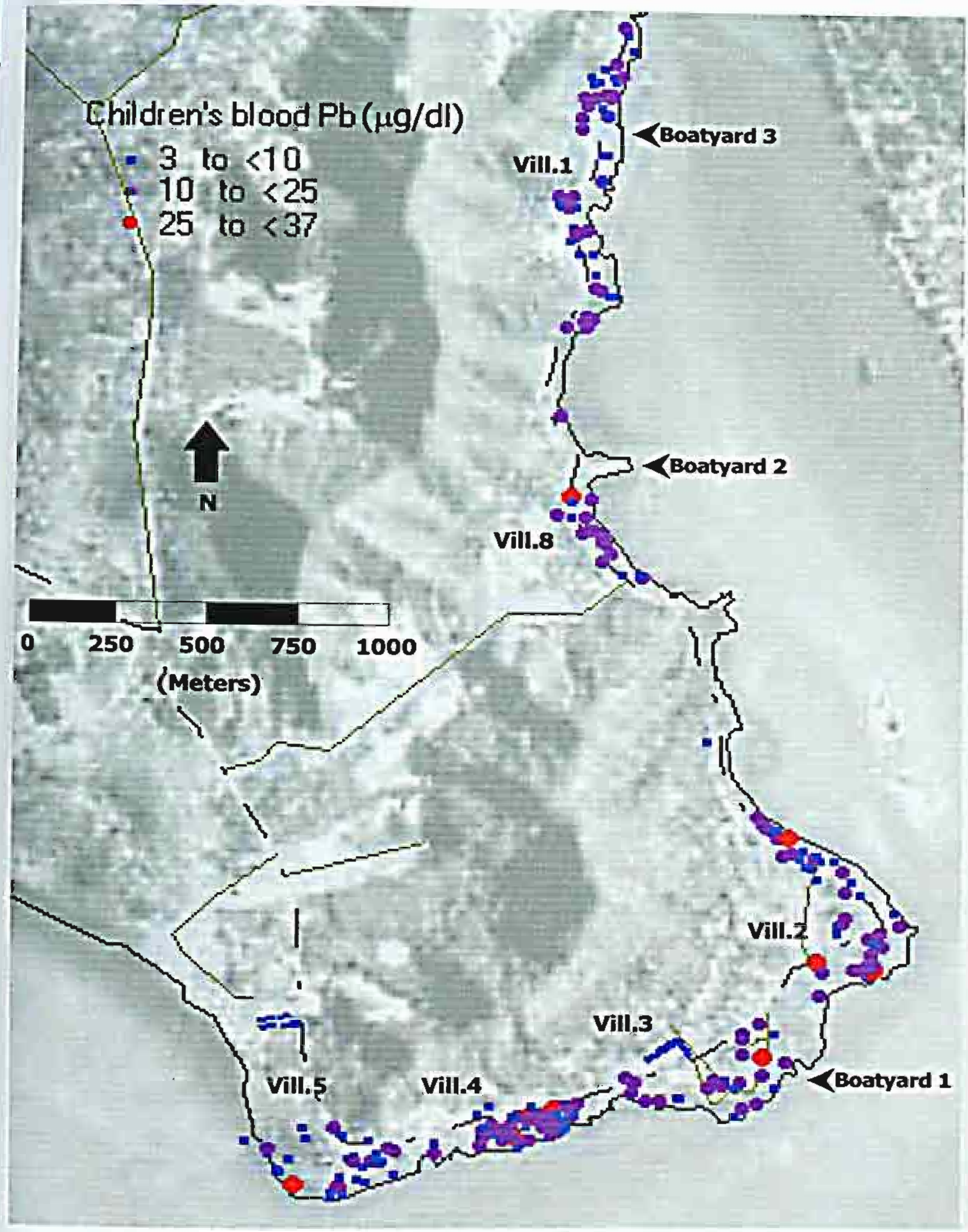


Figure 5.2 The spatial distribution of children's blood lead (according to place of residence).

5.2 Children's blood lead levels according to various potentially contributing factors

Several factors could potentially influence childhood lead contamination in the environs of the boatyards. In this survey, the variables related to environmental lead levels, children's behaviour, geographical features, occupation of family members, and house-condition, were considered as potential explanatory variables of lead contamination in children. The effects of age and sex were first investigated and controlled for in all subsequent analyses, because of the possibility of their confounding the effects of other variables on blood lead level.

As the overall distribution of lead concentration of children's blood in the study was highly skewed to the right, linear regression modeling was undertaken on the logarithm-transformed (base-2) blood lead concentration. The strategy of-analytical investigation was to maintain age and sex in the model from the beginning, then first to examine the effects of distance/direction of the child's home from the nearest boatyard as well as the effects of the frequency with which the child entered any of the boatyards.

These aspects of the boatyard were then removed temporarily, while the relationship of childhood lead with household dust and soil lead were examined, and these variables retained as child-environment contact variables that were related to the children's blood lead were identified.

With the model obtained up to this point, the effects of occupation of any household member in boat-repair work, either within a boatyard of at home were examined, followed by an investigation of particular practices of these boatyard workers, that could potentially have an influence of childhood lead levels.

Finally, the variables specifying distance/direction from the nearest boatyard and frequency of visiting a boatyard were re-introduced to the model to determine if these variables related to proximity to a boatyard could explain any of the remaining variability in the children's blood lead. At each stage, the statistical significance of variables included in the models was assessed by partial F-tests, implemented as the post-estimation *testparm* command in Stata.

The information provided by the resulting model as well as that yielded by the modeling process itself were evaluated.

5.2.1 Children's blood lead levels according to age and sex

Table 5.1 shows the results of modeling of children's blood lead in terms of age and sex. Because of the logarithmic transformation, the coefficients for each term in the model have been re-transformed and expressed as multiplication factors for blood lead concentration. Mean blood lead levels in boys were slightly higher than in girls, and in both sexes generally decreased with increased age after at maximum at the age of 6 to 8 years.

Table 5.1 Univariate regression of children's blood lead levels against age and sex.

Variable	Value	n	Coefficient	Multi-plication factor	95% confidence interval	P-value
Sex/age						
	Male					<0.00005
	4.5 -<6	12	0 [ab]	1		
	6 - <8	30	0.0095 [a]	1.007	0.745 - 1.345	
	8 - <10	41	-0.3669 [bc]	0.774	0.587 - 1.035	
	10 - <12	37	-0.4511 [cd]	0.732	0.548 - 0.972	
	12 - <14	23	-0.5703 [cd]	0.674	0.497 - 0.919	
	Female					
	4.5 -<6	12	-0.2866 [abcd]	0.820	0.578 - 1.163	
	6 - <8	23	-0.1238 [abe]	0.918	0.677 - 1.245	
	8 - <10	44	-0.3150 [bce]	0.804	0.608 - 1.062	
	10 - <12	57	-0.6306 [df]	0.646	0.492 - 0.848	
	12 - <14	39	-0.8513 [f]	0.554	0.418 - 0.735	

Coefficients not having a superscript in common differ significantly at $P < 0.05$. Adjusted coefficient of determination = 0.1216.

5.2.2 Children's blood lead according to distance and direction of residence from the nearest boatyard

Table 5.2 shows the results of regression of children's blood lead levels and distance and direction from the nearest boatyards, adjusted for age and sex. There was a significant difference in children's blood lead contamination in the areas around the 3 boatyards, with children who lived close to boatyard

1 having blood lead levels significantly higher than those living close to other boatyards.

Table 5.2 Regression of children's blood lead levels against spatial variables, adjusted for age and sex.

Variable and values	n	Coefficient	Multi-plication factor	95% confidence interval	P-value
Boatyard					0.0002
Boatyard 1		0 [a]	1		
Boatyard 2		-0.4136 [ab]	0.751	0.533 - 1.057	
Boatyard 3		-0.7022 [b]	0.615	0.485 - 0.779	
Direction/distance from nearest boatyard (change per 100m distance)					
Boatyard 1					<0.00005
West	143	-0.0627 [a]	0.958	0.941 - 0.974	
Northeast	73	-0.0980 [b]	0.934	0.903 - 0.967	
Boatyards 2, 3					0.6150
South	43	0.0980 [abc]	1.068	0.935 - 1.219	
North	59	0.0095 [c]	1.007	0.960 - 1.055	

Coefficients not having a superscript in common differ significantly at $P < 0.05$.
Adjusted coefficient of determination = 0.2124

Children's blood lead decreased significantly with increasing distance from the nearest boatyard in both directions from boatyard 1, at the rates of 4.2 percent per 100 metres to the west and 6.6 percent per 100 metres to the northeast. However, no significant change in children's blood lead was found with distance away from boatyards 2 and 3 in either direction.

5.2.3 Childrens' blood lead according to frequency of entering a boatyard

Children's blood lead level was found to be strongly and significantly related to the frequency with which the children visited a boatyard (Table 5.3a). However, when adjustement was made for distance/direction from the nearest boatyard, this magnitude of this relationship as well as the statistical significance was greatly reduced (Table 5.3b).

Table 5.3a Regression of children's blood lead levels against entering the boatyards, adjusted for age and sex.

Variable and values	n	Coefficient	Multi-plication factor	95% confidence interval	P-value
Going into boatyards					<0.00005
- ≤ 1 time per month	194	0	1		
- > 1 time per month to 1 time per week	70	0.1597	1.117	0.989 - 1.262	
- > 1 time per week	54	0.3780	1.299	1.137 - 1.486	

Adjusted coefficient of determination = 0.1877

Table 5.3b Regression of children's blood lead levels against entering the boatyards, adjusted for age and sex and distance and direction from the nearest boatyard.

Variable and values	n	Coefficient	Multi-plication factor	95% confidence interval	P-value
Going into boatyards					0.2678
- ≤ 1 time per month	194	0	1		
- > 1 time per month to 1 time per week	70	0.0734	1.052	0.929 - 1.192	
- > 1 time per week	54	0.1699	1.125	0.973 - 1.3000	

Adjusted coefficient of determination = 0.2041

5.2.4 Children's blood lead levels according to residential environmental lead levels

Scatter plots of log blood lead against log dust and soil lead are shown in Figure 5.3. Blood lead was moderately and highly significantly correlated with household dust lead but there was no evidence of correlation with soil lead. When these environmental lead levels were included in a regression model together with age and sex, the pattern of relationship persisted (Table 5.4). The model suggested a doubling of household dust lead was related to a 12.5 percent increase in children's mean blood lead.

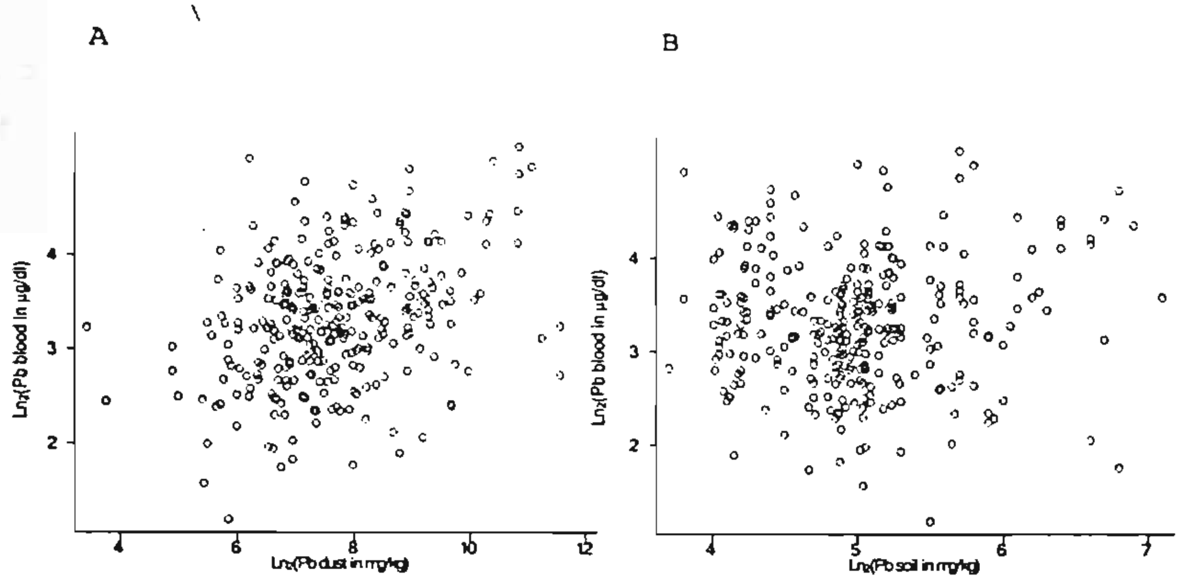


Figure 5.3 Scatter plot of children's blood lead levels and environmental lead levels in base-2 logarithm A) Household dust lead levels B) Soil lead levels.

Table 5.4 Regression of children's blood lead levels against environmental lead level, adjusted for each other and for age and sex.

Variable and values	Coefficient	Multi-plication factor	95% confidence interval	P-value
Household dust lead				<0.00005
Doubling	0.1701	1.125	1.084 - 1.167	
Soil lead				0.9185
Doubling	-0.0057	1.004	0.930 - 1.084	

Adjusted coefficient of determination = 0.2179

5.2.5 Children's blood lead levels according to children's environment-contact behaviour

Comparison of information obtained from the child interview and parent or guardian interview regarding child behaviour revealed some discrepancies. For example, in the question regarding washing of hands before eating, only 42% of guardians gave the same answer as their children. Where differences occurred, the information retrieved from the parent or guardian was used in the analysis.

Table 5.5 shows the results of separate regressions, each adjusted for age and sex and household dust and soil lead levels. Children's blood lead level was significantly higher in children who slept on the floor or on a mat on the floor compared with those sleeping on a bed. Those who played on the ground in front of the house, where shoes are removed, also had significantly higher blood lead levels than other children.

However, significant differences in blood level were not found according to frequency of eating with bare hands, ingestion of non-food items, or playing on the ground in general or swimming in the lake, or according to the regular place for eating meals in the home.

Table 5.5 Regression of children's blood lead levels against child-environment contact variables, each separately adjusted for age, sex and household dust and soil lead levels.

Variable and values	n	Coefficient	Multi-plication factor	95% confidence interval	P-value
Washing hands before eating					0.5396
- > 1 time a week	115	0	1		
- > 1 time a month to 1 time a week	119	-0.0330	0.977	0.877 - 1.089	
- Never/≤ 1 time a month	83	-0.0963	0.935	0.831 - 1.053	
Eating with bare hands					0.7943
- Never/≤ 1 time a month	288	0	1		
- > 1 time a month to 1 time a week	18	0.0285	1.020	0.835 - 1.245	
- > 1 time a week	11	-0.1184	0.921	0.715 - 1.185	
Ingestion of non-food items					0.2758
- Never/≤ 1 time a month	278	0	1		
- > 1 time a month to 1 time a week	36	0.1121	1.081	0.930 - 1.256	
- > 1 time a week	4	0.3999	1.319	0.871 - 1.996	
Eating place					0.2691
- Table	41	0	1		
- Makeshift bed	33	0.1857	1.137	0.940 - 1.376	
- Mat on floor	94	-0.0238	0.984	0.844 - 1.146	
- Floor	150	0.0861	1.061	0.917 - 1.229	

Table 5.5 (continued)

Variable and values	n	Coefficient	Multi-plication factor	95% confidence interval	P-value
Sleeping place					0.0109
- Bed	38	0	1		
- Mattress	266	0.1903	1.141	0.988 - 1.317	
- Floor, mat	14	0.5773	1.492	1.149 - 1.937	
Playing on the ground					0.1851
- Never/≤ 1 time a month	192	0	1		
- > 1 time a month to 1 time a week	41	-0.0714	0.952	0.824 - 1.099	
- > 1 time a week	85	0.1234	1.089	0.975 - 1.217	
Swimming in the lake					0.3831
- Never/≤ 1 time a month	114	0	1		
- > 1 time a month to 1 time a week	46	0.1249	1.090	0.940 - 1.265	
- >-1 time a week	158	0.0881	1.063	0.960 - 1.177	
Playing on ground in front of the house					0.0001
- No	112	0	1		
- Yes	206	0.2833	1.217	1.106 - 1.339	

Subsequently the two child-environment contact variables found to have a relationship with blood lead above were fitted together, along with age and sex in a single regression model. Both retained their statistical significance, with little change in the magnitude of their coefficients (Table 5.6).

Table 5.6 Regression of children's blood lead levels against child-environment contact variables with evidence of association in previous set of models, adjusted for each other and for age, sex and household dust and soil lead levels.

Variable and values	n	Coefficient	Multi-plication factor	95% confidence interval	P-value
Sleeping place					0.0357
- Bed	38	0	1		
- Mattress	266	0.1606	1.118	0.971 - 1.287	
- Floor, mat	14	0.4885	1.403	1.084 - 1.816	
Playing on ground in front of the house					0.0002
- No	112	0	1		
- Yes	206	0.2602	1.198	1.089 - 1.318	

Adjusted coefficient of determination = 0.2670

5.2.6 Children's blood lead levels according to occupation of household members in boat-repair work and the practices of those workers

Table 5.7 shows the results of including the presence of household members engaged in boat-repair work in a regression model already including age, sex, dust and soil lead levels and the two child-environment contact variables identified above. Neither variable reaches statistical significance, although the magnitude of the coefficient and the rather low p-value for having a household member work in a boatyard suggest there may be some relationship. The role of family members' occupation in boat-repair work was therefore explored further, by considering the particular practices of these workers.

Table 5.7 Regression of children's blood lead levels against occupation of household members inn boat-repair work, adjusted for each other and for age, sex, household dust and soil lead levels, and child-environment contact variables (sleeping place and playing in front of the house).

Variable and values	n	Coefficient	Multi-plication factor	95% confidence interval	P-value
Boatyard worker in household					0.0904
- No	271	0	1		
- Yes	47	0.1726	1.127	0.981 - 1.295	
Boat-repair at home					0.5558
- No	199	0	1		
- Yes	119	0.0407	1.029	0.936 - 1.130	

Adjusted coefficient of determination = 0.2703

Occupation in boat-repair work in a boatyard and repairing boats at the home were not mutually exclusive activities. Twenty four of the 47 households (51%) that included a boatyard workers among its members also undertook boat-repair at home, as did 95 of the 271 household (35%) that did not include a boatyard worker (Table 5.8).

Table 5.8 Potential home contamination behaviours according to type of boat repair occupation undertaken by household members of index children. Numbers in the table are the numbers of children.

Occupation in boat-repair		n	Keep repair equipment/ materials at home	Keep Pb_3O_4 at home	Change work clothes in the house	Delay bathing after return from work	Repair boats at home > once a month
At boat-yard	At home						
Yes	Yes	24	19	16	10	13	14
Yes	No	23	1	0	7	6	
No	Yes	95	32	26			57
No	No	176	0	0			
Total		318	52	42	17	19	71

Most of the households undertaking boat-repair at the home (42/51, 82%) kept boat-repair equipment and/materials or lead oxide (Pb_3O_4) in the home, as did one of the households with a boatyard worker who did not do boat-repair at home. Seventy one of the 119 households undertaking boat-repair at home (60%) did so on more than one boat per month. Among the 47 boatyard workers, 17 (36%) changed out of their working clothes inside the house and 19 (40%)

delayed bathing for at least half an hour after arriving home from work. The distributions of these practices are shown in Table 5.8.

In order to examine the contribution, if any, of boat-repair worker practices to the model explaining children's blood lead level, boat-repair work was grouped into three variables, namely, any boat-repair work (either in a boat-yard or at home), the practice of keeping boat-repair equipment or materials or lead oxide in the home, and delaying bathing on return from work or changing our of work clothes inside the house. These variables were fitted to a regression model containing age and sex of the child, household dust and soil lead levels, and child-environment contact variables (sleeping place and playing in front of the house). The results of the boat-repair variables in this model are shown in Table 5.9.

As the variable for any boat-repair work by household members is included in the model, the coefficients for keeping equipment/materials/lead oxide in the home and for delayed bathing or changing clothes in the home represent the effect of these particular practices on children's blood lead, rather than a global effect of there being a boat-repair worker in the household.

Table 5.9 Regression of children's blood lead levels against potential risk behaviours related to boat repair by household members, adjusted for each other and for age, sex, household dust and soil lead levels, and child-environment contact variables (sleeping place and playing in front of the house).

Variable and values	N	Coefficient	Multiplication factor	95% confidence interval	P-value
Any boat-repair work	142	-0.0473	0.968	0.861 - 1.087	0.5800
Any keeping of boat-repairing equipment and/or Pb_3O_4 at home	56	0.2254	1.169	1.007 - 1.376	0.0405
Delayed bathing or changing work clothes inside home on return from work	24	0.2636	1.200	1.004 - 1.436	0.0454

Adjusted coefficient of variation = 0.2829

These is some evidence that keeping boat-repair equipment/ material or lead oxide in the home, as well as delaying bathing or changing work clothes in the home do influence the level of lead in children's blood, although explaining very little of the variation in children's blood after considering the biological, environmental, and child behavioural variables already considered.

5.2.7 Remaining effects of proximity to a boatyard on children's blood lead level

Adding distance/direction from the nearest boatyard (P=0.0655) or frequency of children's entering a boatyard (P=0.3448) to the model developed up the stage in the previous subsection, failed to significantly improve the fit of the model. However, the low P-value for distance and direction from the nearest boatyard indicates some weak evidence for remaining influence of spatial location on children's blood lead level.

5.2.8 Independent influences of biological, environmental, behavioural and occupational variables on children's blood lead level

The parameters of the model containing biological variables (age and sex), environmental variables (household dust and soil lead level), behvioural variables (child's sleeping place, playing on the ground in front of the house) and occupational variables(boat-repair related practices by household members) are displayed in Table 5.10.

Evidence for an effect of age and sex, household dust lead level and child-environment contact behaviour is very strong, while that for boat-repair practices is somewhat weaker. This model indicates that a doubling of household dust lead level is associated with a 9.3 percent increase in mean children's blood lead level, that sleeping close to the floor, either directly or only on a mat, rather than on a bed results in an increase of 50 percent and playing on the ground in front of the house a 26 percent increase.

In addition, according to the model, the increases in children's mean blood lead resulting associated with keeping boat-repair equipment/materials/lead oxide at home is 22 percent and that from boat-repair workers delaying bathing or changing work clothes in the home is 26 percent.

The confidence intervals for the occupational practices and sleeping place are wide, so that the point estimates should be considered with caution. Furthermore, much of the variability of children's blood lead level remains unexplained. The model explains only about 28 percent of the variation in children's blood lead content. Nevertheless, the model appears to be well specified, judging from the residual plot (Figure 5.4).

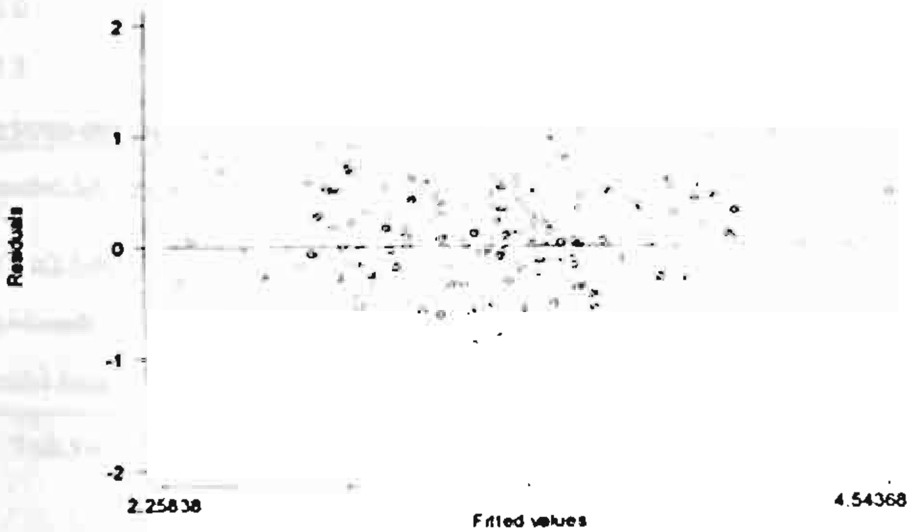


Figure 5.4 Residual plot of the model of Table 5.10.

Table 5.10 Multivariate regression of children's blood lead levels showing independent effects of sex and age, household dust and soil lead level, child-environment contact, and activities related to boat-repair by household members potential risk behaviours related to boat repair by household members.

GROUP: Variable Value	n	Coeff-icient	Multipl-ication factor	95% confidence interval	[1]P-value	[2]P-value
BIOLOGICAL:						<0.00005
Sex & age (yr)						
M 4.5 - <6	12	0 [acd]	1			
M 6 - <8	30	0.1937 [ab]	1.144	0.874 - 1.496		
M 8 - <10	41	-0.1028 [cd]	0.931	0.716 - 1.211		
M 10 - <12	37	-0.2399 [cdef]	0.847	0.651 - 1.102		
M 12 - <14	23	-0.4652 [eh]	0.724	0.548 - 0.958		
F 4.5 - <6	12	-0.1426 [bdf]	0.906	0.658 - 1.248		
F 6 - <8	23	0.0269 [bd]	1.012	0.764 - 1.340		
F 8 - <10	44	-0.1318 [d]	0.913	0.707 - 1.179		
F 10 - <12	57	-0.3991 [fh]	0.758	0.590 - 0.975		
F 12 - <14	39	-0.5777 [h]	0.670	0.516 - 0.870		
ENVIRONMENTAL:						<0.00005
Household dust lead					<0.00005	
Doubling		0.1287	1.093	1.052 - 1.136		
Soil-lead					0.4007	
Doubling		-0.0501	0.966	0.891 - 1.048		

Table 5.10 continued on following page

Table 5.10 (continued)

GROUP: Variable Value	n	Coeff-icient	Multipl-ication factor	95% confidence interval	[1]P-value	[2]P-value
CHILD-ENVIRONMENT CONTACT:						<0.00005
Sleeping place					0.0297	
Bed	38	0 [a]	1			
Mattress	266	0.1640 [a]	1.120	0.975 - 1.827		
Floor, mat	14	0.4994 [b]	1.414	1.094 - 1.827		
Playing on ground in front of the house					0.0002	
No	112	0	1			
Yes	206	0.2592	1.197	1.089 - 1.316		
BOAT-REPAIR RELATED ACTIVITY:						0.0229
Any boat-repair work vs. not	142	-0.0473	0.968	0.861 - 1.087	0.5800	
Keeping of boat-repairing equipment and/or Pb_3O_4 at home vs. not	56	0.2254	1.169	1.007 - 1.376	0.0405	
Delayed bathing or changing work clothes inside home on return from work vs. not	24	0.2636	1.200	1.004 - 1.436	0.0454	

[1] P-value for variable; [2] P-value for group. Coefficients for values within a variable which do not have any superscript letter in common differ significantly ($P < 0.05$). Adjusted coefficient of variation = 0.2829.

5.3 Evaluation

This study has confirmed that children's blood lead levels follows the level of lead in household dust in the study area, while showing no significant relationship with soil lead levels. One possible explanation is that exposure to household dust may be more intimate, frequent or prolonged than that to soil. The more readily detectable presence of soil on skin and surfaces with which children come into contact may result in a greater concern with washing skin and surfaces dirtied with soil. However, an alternative explanation could be that child contamination is partly or largely mediated via the direct inhalation of air-borne particles of plumboplumbic oxide blown into the area surrounding the boatyards - the process which is most likely responsible for the spatial pattern of lead in household dust. This pattern comprises high levels of lead close to each boatyard and an approximately exponential fall-off with increasing distance.

Several other studies have shown a close relationship between dust lead and children's blood lead levels [34;74-77]. However, soil lead has also been shown in some studies to be related to childhood blood lead [3;12;38;61;74;78], but in none of those studies was the source of lead the same as in the current study. A weakness in our study is that soil lead content was determined in specimens collected between 16 and 17 weeks after the blood specimens were taken. This delay, together with the postulated half-life of blood lead of around 90 days and the possibility of the lead content of surface soil varying over relatively short time periods, might have weakened our ability to detect an association between blood and soil lead.

Nevertheless, in view of the lack of any demonstrable association between blood lead and soil lead, it is surprising that such a marked increase in blood lead was apparent among children who played on the ground in front of their house. Although not all houses have bare earth at this place, one may imagine that this behaviour would bring children into close contact with soil. Perhaps the fact that people routinely remove their shoes in front of the house could result in soil from distant areas adhering to the shoes being shaken loose in this place. On the other hand, the finding that sleeping close to the floor is associated with elevated blood lead levels is consistent with household dust being a major source of childhood lead contamination.

There was no statistically significant relationship between children blood lead levels and distance and direction from the nearest boatyard of each household, after household dust lead levels were adjusted for. This is probably due to household dust acting as an intermediate in the pathway of association between distance and direction from the nearest boatyard seen in the crude analysis.

CHAPTER 6: General discussion

This study was undertaken with the main aim of assessing the extent to which the use of plumboplumbic oxide (Pb_3O_4) in the boat-repair industry contributed to soil and dust and childhood lead contamination in the surrounding area.

Household dust lead was found to fall-off somewhat exponentially with distance from the boatyards and to be a strong determinant of children's blood lead level. Occupation of household members in boat-repair work was also strongly associated with elevated household lead and there was some evidence that the practice of workers keeping boat-repair materials of equipment at home and of changing work clothes at home or delaying bathing after work were independently associated with increased blood levels in children in the home.

Overall, in our study sample approximately 50 percent of children had a PbB equal to or exceeding 10 µg/dl which has been set as the minimum level of concern by the Centers for Disease Control, USA, in 1991, above which levels can lead to adverse health effects, such as impaired neurological function and behavioural alterations in children[79;80]. These results indicate a problem of lead contamination of sufficient magnitude to be of public health concern.

Environmental lead patterns and relationships

The concentration of lead in soil and household dust, sampled within 2 kilometres of any one of the boatyards, have wide ranges. Considering the level of concern of lead in household dust and soil at 150 mg/kg, the majority (60%) of households had dust lead levels exceeding or equal to this value, compared with only fifteen percent of soil specimens. Nevertheless, in some areas, soil lead concentrations were extremely high (more than 5,000 mg/kg).

The distribution of lead in soil and household dust were loosely related (maximum correlation coefficient 0.131), suggesting that lead in soil may become airborne and settle in the household, or that both may be the result of airborne spread. However, there may be a number of other factors involved, as the spatial distribution of lead in soil generally did not match that of lead in household dust. Thus soil lead is unlikely to be the main contributor to lead in household dust. Lead in soil may be more vulnerable to other influencing factors such as leaching and disturbance from vehicles, animals, humans etc. To capture the full variability of soil lead in which there appeared to be considerable short-range variability would have required a much larger number of specimens[81]. Among other studies of the environmental distribution of lead, both correlations and no correlations between dust and soil lead have been reported[4,82].

Unlike soil lead, mean household dust lead showed clear evidence of dependence on distance from each boatyard, with an exponential fall off in most directions fitting the data reasonably well. Similar fall-off of household lead levels with distance have been described in the area surrounding lead smelters[13;29;93].

Our data indicate that that, at all distances, the variation in dust lead was wide, and the statistical model suggests that at least 5 percent of unacceptably high levels (considered here as levels above 150 mg/kg) could occur up to distances of 2.8 kilometres from a boatyard (based on the rate of fall-off as modeled to the west of boatyard 1), even in households where none of the members is engaged in boat-repair work.

Where household members were engaged in boat-repair work, household dust lead levels were greatly elevated - up to a mean of 65 percent in the case of boatyard workers. Presumably this is a result of workers inadvertently transferring lead oxide from the workplace to the home on clothes, shoes, skin, hair etc. Similar examples of take-home lead have been reported in other settings[41;84;85].

Childhood blood lead levels and their relationship with environmental lead

The association between environmental lead and children's blood lead levels was assessed by multivariate linear regression analysis. Results from the analysis suggest that there is a significant relation between childhood lead contamination and deposited household dust lead levels but no association with soil lead. Several other studies have shown a close relationship between dust lead and children's blood lead levels[19;78;86;87]. The crude relationship between incrasing distance from a boatyard and decreasing children's blood lead seems to be explained almost entirely by the fall-off in household dust levels, as the relationship was drastically reduced when soil lead was adjusted for.

Possible explanations for the close relationship between blood lead and dust and the lack of a relationship with soil dust were suggested in the previous chapter - that of personal surface contamination with dust, especially small particles such as those of plumbplumbic oxide, being less obvious than that with soil, as well as the possible more frequent or prolonged exposure to household dust, and the possibility of inhaling dust particles, which, even if not small enough to enter the smaller airways, could nevertheless be accumulated in the oropharynx and subsequently swallowed. Particle diameter analysis of the plumboplumbic oxide revealed over 50 percent of the volume to comprise particles less than 20µm in diameter, which marks them as having a high degree of bioavailability[74]. Ninety-eight percent of the volume comprised particles within the range of about 2µm to 76µm, which is small enough for them to readily become attached to surfaces. Particles which are less than 250µm have been reported to be more likely than larger particles to stick to hands, shoes, pets, toys and other objects[88].

The statistical model developed for children's blood lead level suggests an average of almost 10 percent increase in blood lead for a doubling of household dust lead. While this may appear to be a small increase, it should be noted that the levels of household dust lead ranged from close to 10 mg/kg up to about 3000 mg/kg - more than an 8-fold doubling of dust lead, or a doubling of blood lead. Furthermore, sleeping close to the floor - which presumably may bring the child into closer contact with household dust - was itself associated with a 26 to 41 percent increase in blood lead levels (compared to sleeping on a mattress on the floor or on a bed, respectively). It may be surmised that a mat on the floor might act as a reservoir of lead-laden dust, as it may be more difficult to clean than the floor itself. Indeed, in another setting carpets and rugs were shown to serve as large reservoirs for house dust[2], thus, where household dust lead levels are already high, they are expected to be a major source of childhood lead contamination.

Besides the less than ideal temporal relationship between the collection of blood and soil specimens in this study, the high spatial variability seen in measures of soil lead, together with the fact that soil lead at household positions was interpolated from the sampling grid and thereby subject to error, may be additional factors mitigating against the finding of an association between children's blood lead levels and soil lead. Furthermore, it is likely that children come into contact with soil not only at the location of their residence but also at many other locations, as they move around the area, going to school, playing with other children, etc. If so, then a strong spatial correlation may not be expected. In this regard it is perhaps of relevance that playing on the ground in front of the house was strongly associated, both in magnitude and in statistical significance, with elevated blood lead levels. This position is where people routinely remove their shoes before entering the house and could result in soil, adhering to the shoes from distant locations, being shaken loose in this place. Measurements of lead in these positions and at other points around the households would be useful to any attempt to confirm this hypothesis. Playing close to the ground in general, as well as hand-to-mouth activities, have been found elsewhere such as in mining areas[28;89] and in a high-traffic-volume area to be associated with lead contamination of children[90], and many studies have also shown significant relationships between soil lead and childhood blood lead levels in settings where Superfund deposits or mining were the major sources of environmental contamination[35;91;92].

Implications of the procedures used to collect and analyze household dust specimens

In this study, dust from little disturbed areas was collected using the method of brushing lightly with a new toothbrush onto a clean paper sheet. Many other studies have collected dust by vacuum or wipe methods, and have mostly focused on the relationship of children's blood lead levels and household dust lead loading (the weight of lead present per unit surface area in a certain time period). Many of these studies found associations between house dust lead loading and childhood lead contamination[92-94], but others found no such relationship[95]. In our study, neither time nor surface area were considered, so that the measure was purely that of lead content of the dust, and should reflect the contamination of lead in the household over some period of time. This may be a good indication of exposure to lead in the house over a prolonged period. The measurement of dust lead in this way also has some practical advantages over other methods, including low cost, taking only a few minutes to collect, no requirement for power source or equipment, and no problem of householder cleaning prior to the sampling visit, etc. Laxen (1987)[19] and Sutton (1995)[40] reported that dust lead concentration was a cost-effective parameter for predicting blood lead compared to lead loading. It would be of some interest to investigate whether the lead concentration in the dust itself, or the rate of deposition of lead as dust more closely influences the magnitude of childhood blood lead level in the setting of a boat-repair area.

Other risk factors for childhood lead contamination

Other behavioural risk factors which have been shown in other studies to be related to increased childhood blood lead levels, such as not washing hands before eating, hand-to-mouth activity, and ingesting soil and dust[1;35;96;97] were not identified in our study as risk behaviours. In this respect, our findings are similar to those of Gallapher (1984)[37], who found no relation between blood lead and pica when assessed by a questionnaire.

The relationship between age and blood lead levels has been investigated in several studies, in which lead levels decrease with increasing age following a peak in early childhood (age range 1 to 4 years) has commonly been reported[29;37;99] and our study population showed a similar general pattern, but with a peak in the 6 to 8 year age range. Girls' blood lead levels were slightly lower than those of than boys at a corresponding age. The study of Rabinowitz (1985)[99] suggested that there was no significant difference between the sexes in blood levels at birth to 2 years. While boys may be more likely to be exposed to environmental lead, such as by more frequently playing close to the ground than girls, this cannot be the full explanation for the sex difference as the differential between boys and girls persisted in regression models adjusted for this activity.

While the data obtained in this study and their analysis strongly indicate that plumboplumbic oxide from boat repair activities was the major source of household dust lead contamination in the study area, and that household dust was a major contributor to children's lead contamination, there may have been additional sources contributing to childhood lead burden. Observations in the study area revealed some households where children were engaged in assisting with the repair of fishing nets. This activity involves the manual removal and application of lead sinkers, which may be presumed to result in lead contamination of their hands. Lead sinkers used in fishing have been attributed with causing lead poisoning of other organisms, from which lead could possibly enter the food chain in Canada, where 28% of the waterbird, *Gavia immer*, died from lead poisoning due to ingestion of fishing sinkers[100]. Another possible source or pathway of childhood lead contamination could be the scavenging activities of young boys, picking up scrap metal from boatyards on the weekend. However, the magnitude of such contribution may not have been obviously recognizable owing to the small number of cases.

Other possible contributors to childhood lead contamination that have been identified in other situations, such as taking so-called "herbal" medicines[65;101] and parental smoking[102], were not examined in this study. Parental smoking could possible modify the effect of household dust lead as a source of childhood lead contamination.

The wider context

Although this study was not designed to detect the contamination of lead in the water and sediment in Songkhla Lagoon, nevertheless our observations strongly suggest that the lagoon may be contaminated with lead as a consequence of run-off or leaching of lead-contaminated land, especially that in the boatyards themselves, following rain. Moreover, the shipyard industry was identified as one of the contributors to lead in the environment such as in marine water at Elliott Bay, Washington, adjacent to operating shipyard[103] and in surface sediment from northeastern Marmara Sea close to shipyards and metal smelters[104]. Dissolved lead has been found to accumulate in both exoskeleton and internal tissues of shrimp (*Palaemonetes varians*)[105] and mussel (*Mytilus galloprovincialis*)[106]. As Songkha Lagoon is a rich resource for fishery and aquaculture of prawn, sea bass and seaweed, the levels of lead contamination associated with boat-repair and boat-building activities should be of considerable concern.

Conclusions

In conclusion, childhood blood lead levels are strongly influenced by the level of lead in household dust, which is likely to represent an important proximate source of childhood lead contamination in this setting. Household dust level, itself, is closely associated with proximity to a boatyard and occupation of household members related to boat repair. Lead contamination of children is elevated among children who have closer contact with the environment, either by sleeping close to the floor or playing in the area in front of the house. The range of household dust levels may include levels that are higher than acceptable (150 mg/kg) for distances of up to at least 2.8 km from a boatyard where plumboplumbic oxide is employed, even in the absence of a boat-repair worker in the home.

Implications

This study has shown that environmental and childhood lead contamination are spatially associated with the boat-repair industry, strongly implying that this industry is a source of lead among children living in adjacent communities.

The Department of Industrial Works, Ministry of Industry, reported more than 200 boat building and boat repair yards throughout Thailand[107]. It is likely that all or most of those use a similar process for caulking the boats. Some of these boatyards are located close to residential communities, which are therefore at risk of lead contamination.

Furthermore, from the informal documents on the Internet (such as traditional boat-builder forum: *http://www.ybw.com*, wooden boat suppliers: *http://www.tradboats.com/conseamfillers.html*), red lead (Pb_3O_4) is or has been used worldwide in the wooden-boat building and repair industry as a cementing material, referred to as "red lead putty", which is a mixture of powdered calcium carbonate, boiled linseed oil and lead compound. Therefore, the wooden-boat repair and building industry throughout the world may have accounted for past lead contamination in humans and the environment. The use of wooden boats, nowadays, is still extensive in south and south-east Asia, and still exists in parts of Canada (Ventura Harbor Boatyard) and UK (Lincombe Boatyard). The problem of continuing associated environmental and human lead contamination may be significant in these regions.

Recommendations

The findings of this study indicate that children living close to a boatyard where plumboplumbic oxide is used are likely to have elevated blood lead levels, and that these levels of childhood lead are related to the level of household dust. Household dust levels are higher closer to the boatyard but also increased in household where an occupant is a worker in the boatyard or where small-boat repair work is conducted at home. Thus, an appropriate way to reduce childhood blood lead levels is to reduce lead contamination in household dust, which in turn means either reducing the amount of plumboplumbic oxide used in the boat building/repair industry or reducing its spread to the surrounding area. The following suggestions might be applied in order to mitigate the risk of childhood lead contamination.

The use of plumboplumbic oxide in boat building and repair industry might be replaced by an alternative, less toxic, substance. Simple replacement of plumboplumbic oxide in the traditional process requires that the precise role or roles of plumboplumbic oxide in the caulking mixture be identified. Possible functions of plumboplumbic oxide are acting as an astringent on the wood surface and retarding wood decay (Ray, *http://www.star-distributing.com*). On the other hand the entire process may be modified. One modification which is already in use to a limited extent in Thai boatyards is to use epoxy resin in place of the final plumboplumbic oxide-based coating paste. Currently, this does not avoid the use of lead entirely, as a caulking material of dammar and linseed oil and plumboplumbic oxide is still used prior to the epoxy finish. Advantages of the epoxy finish are that boats can go for longer before needing repair (about 2 years compared with yearly), whereas a disadvantage, according to several boat-owners, is that the repair cost is almost twice that of the traditional process. As a result, the epoxy process is still not widely used in southern Thailand. Polyester and vinylester resins are other alternative substances that can be used in the boat repairing process.

Immediate steps which could be undertaken to reduce the hazard posed by lead contamination include the following:

1. To reduce the dispersal of plumboplumbic oxide into the surrounding environment, more care should be taken in the handling of plumboplumbic oxide. The unmixed, powder form of plumboplumbic oxide should, perhaps, be handled only in a closed and wind-free area, particularly during mixing with cotton fibre and in the mixing of the red lead paste. Of particular importance is the need for suitable disposal measures or plumboplumbic oxide waste and for the effective clean-up of accidental spillages of plumboplumbic oxide.

2. To reduce the transfer of dust lead from the boatyard into the household, workers should be advised to change their clothes and shoes before going home. Moreover, boat-repair workers should be encouraged to avoid inhaling dust by wearing gloves and dust masks, and drinking or eating close to the work place.

3. To reduce the settlement and accumulation of dust-containing lead in the household, particularly if the household is located

less than 2 or 3 kilometres from a boat-yard, family members should be educated regarding need for the common hygiene practices such as frequent wet mopping of floors, dusting off of mats and mattresses used for sleeping, wet-cleaning of windowsills and ceilings, and frequent washing of the shoes-off area at the entrance to the house.

4. Boat-repair workers should be advised to avoid keeping boat-repair equipment and materials at their home, and should take care to remove and discard their work clothes in a part of the house to which children do not have access.

Future considerations

This study has provided some understanding of the static distribution of lead in the local environment and resident child population in an area of boat repair activity. It has also thrown up some clues regarding the proximate sources of this contamination. However, elucidation of the precise pathways underlying the transfer of lead from place to place within the environment, and especially that from the outside environment into the home, requires additional study. An additional issue concerns the transfer of lead into the adjacent water body. With boat-repair yards generally situated on estuaries, the spread of lead both out to sea and upstream may well exceed by far the direct spread on land that has been the focus of the current study. Lead in the open environment, whether on land, water-borne or contained in sediment, also poses a hazard of lead entry into the food chain. The extent to which the boat-repair industry is contributing to this process is another issue towards which attention should be directed.

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