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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

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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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;28;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.

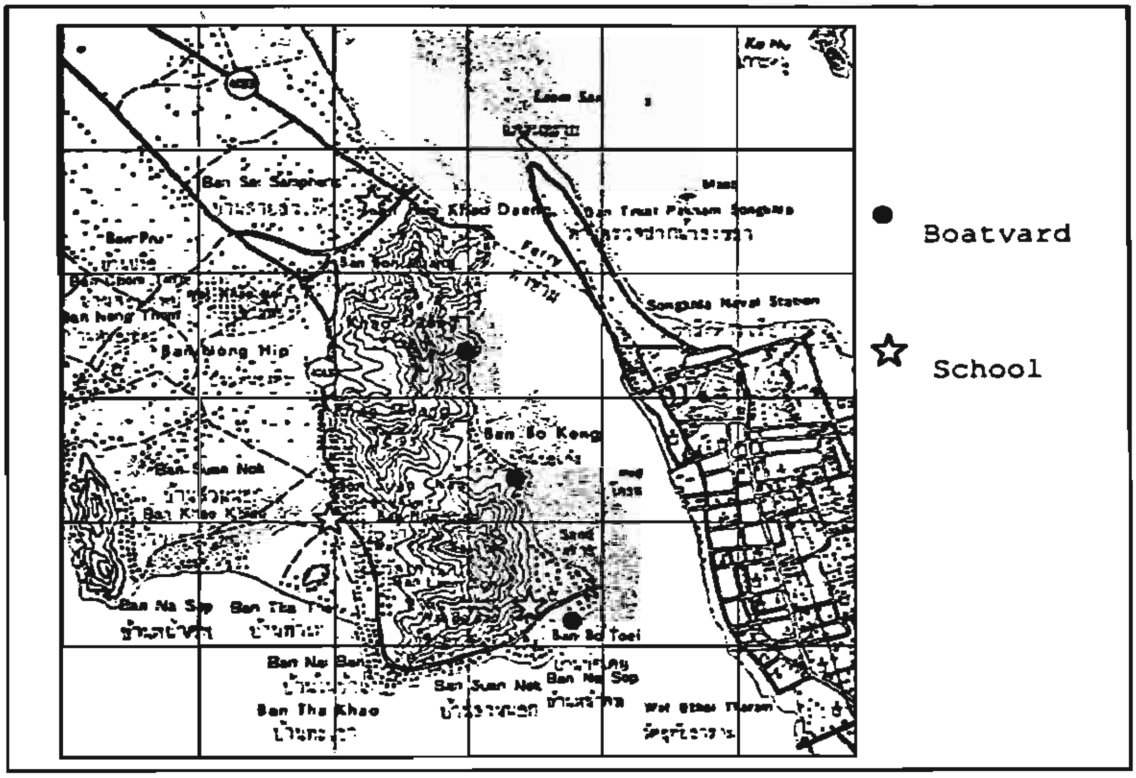
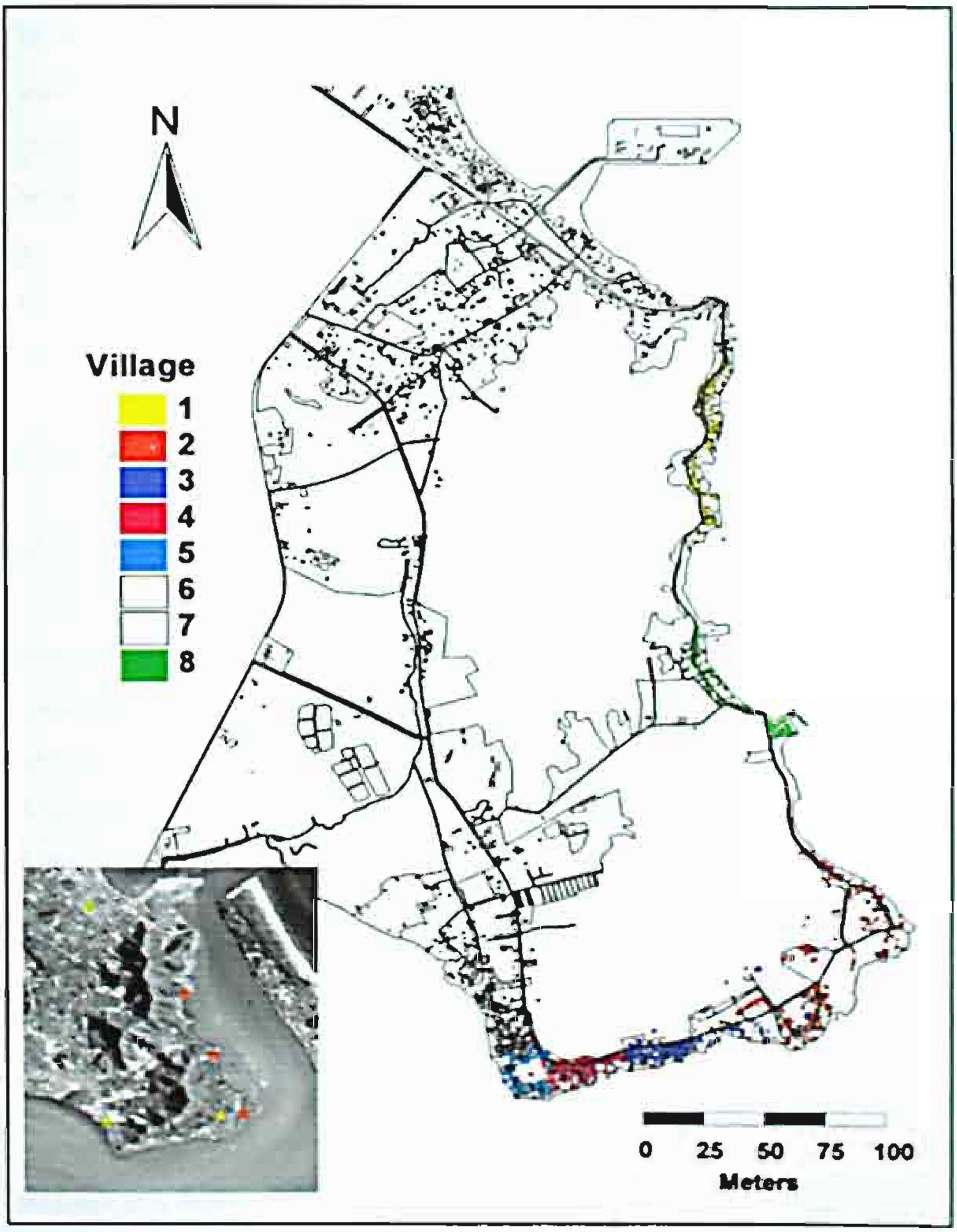


Figure 2.1 Map of the study area, Hua Khao Sub-district, Singhanakhon District, Songkhla Province.

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.

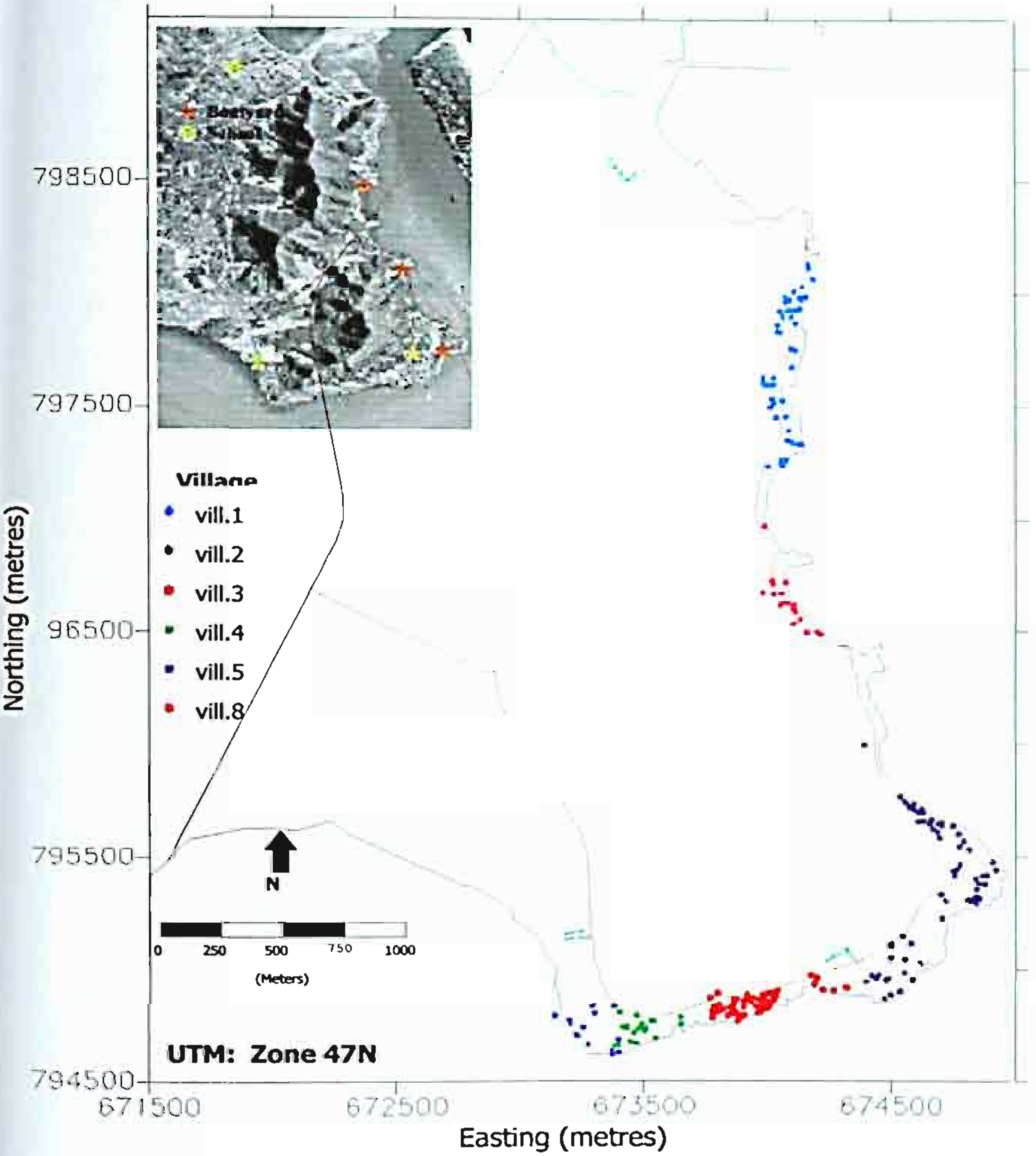


Figure 3.1 Map of the study area, the position of subjects' household in village 1, 2, 3, 4, 5 and 8.

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/$\leq$ 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/$\leq$ 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.

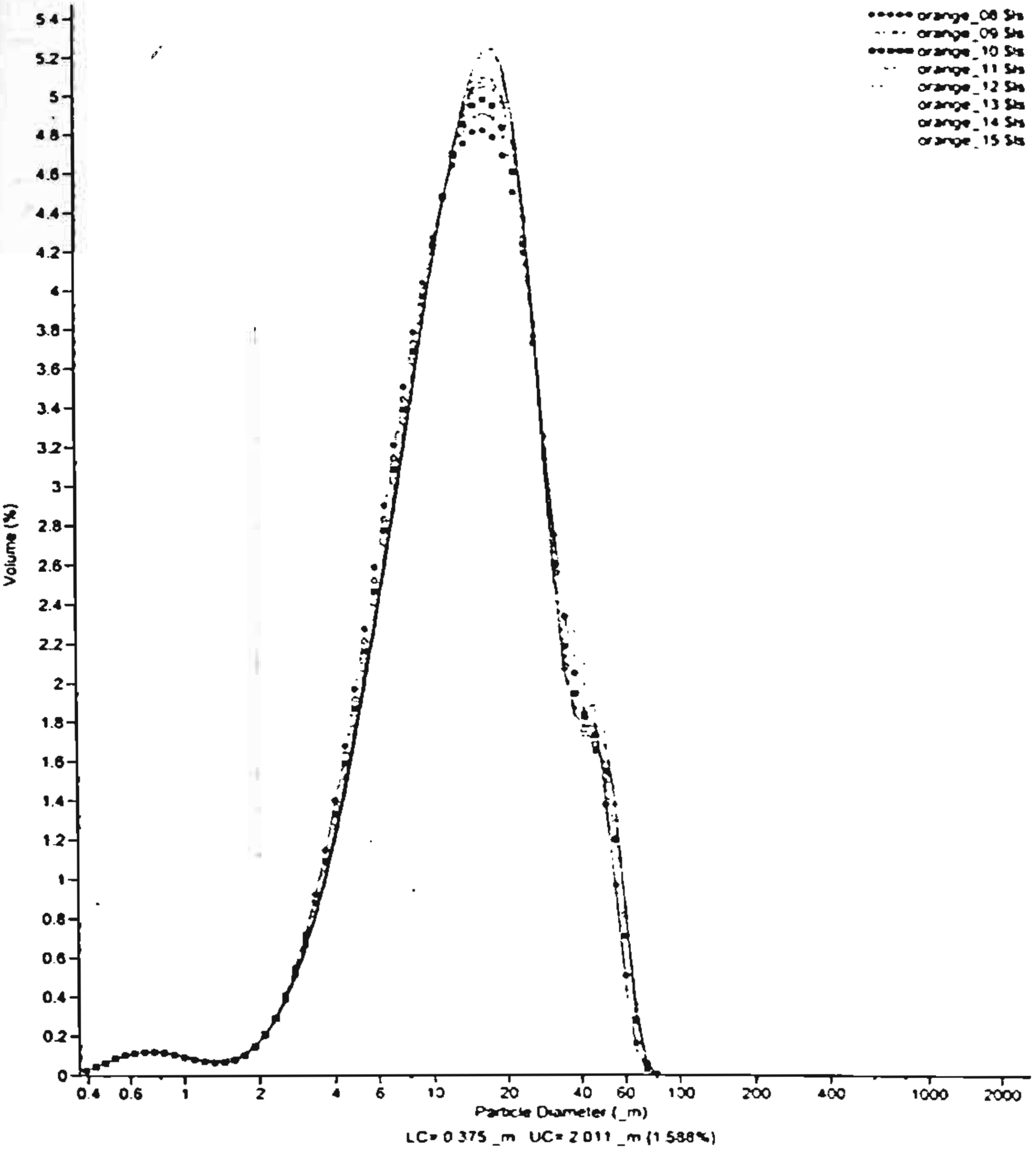


Figure 3.2 Frequency distribution of particle diameter of plumbo-plumbic oxide.

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.

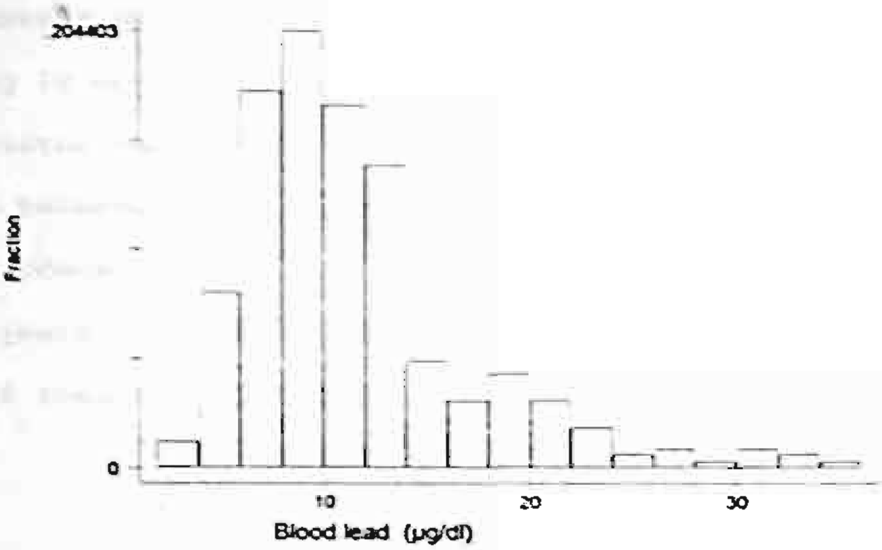


Figure 3.3 Distribution of children's blood lead concentration

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).

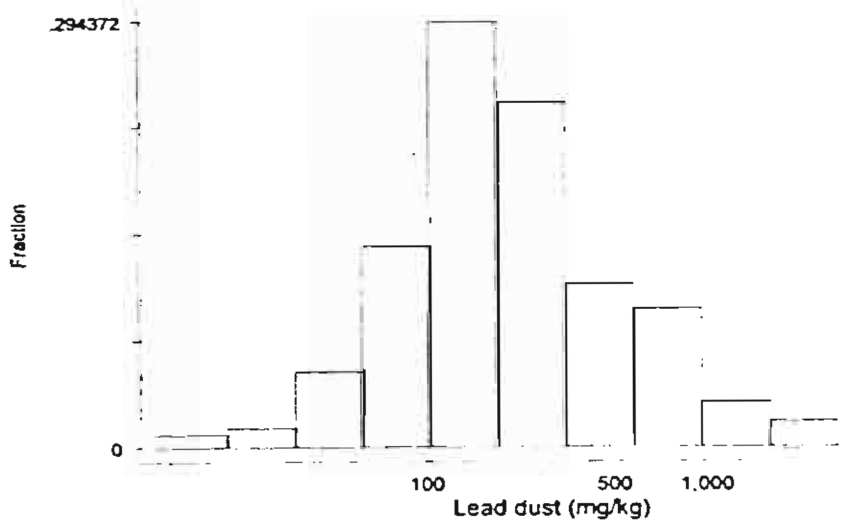


Figure 3.4 Distribution of household dust lead concentration (base-2-logarithm).

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).

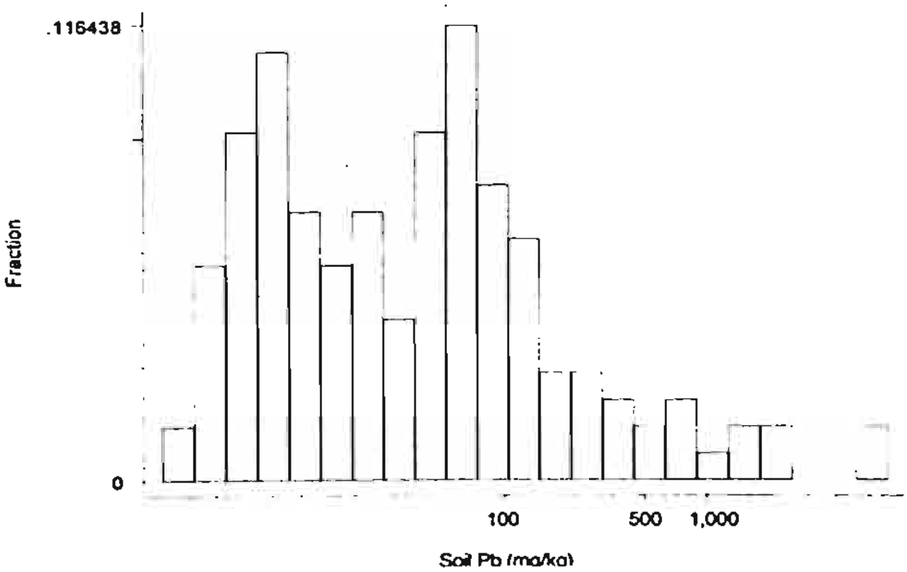


Figure 3.5 Distribution of soil lead concentration (base-2-logarithm).

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).

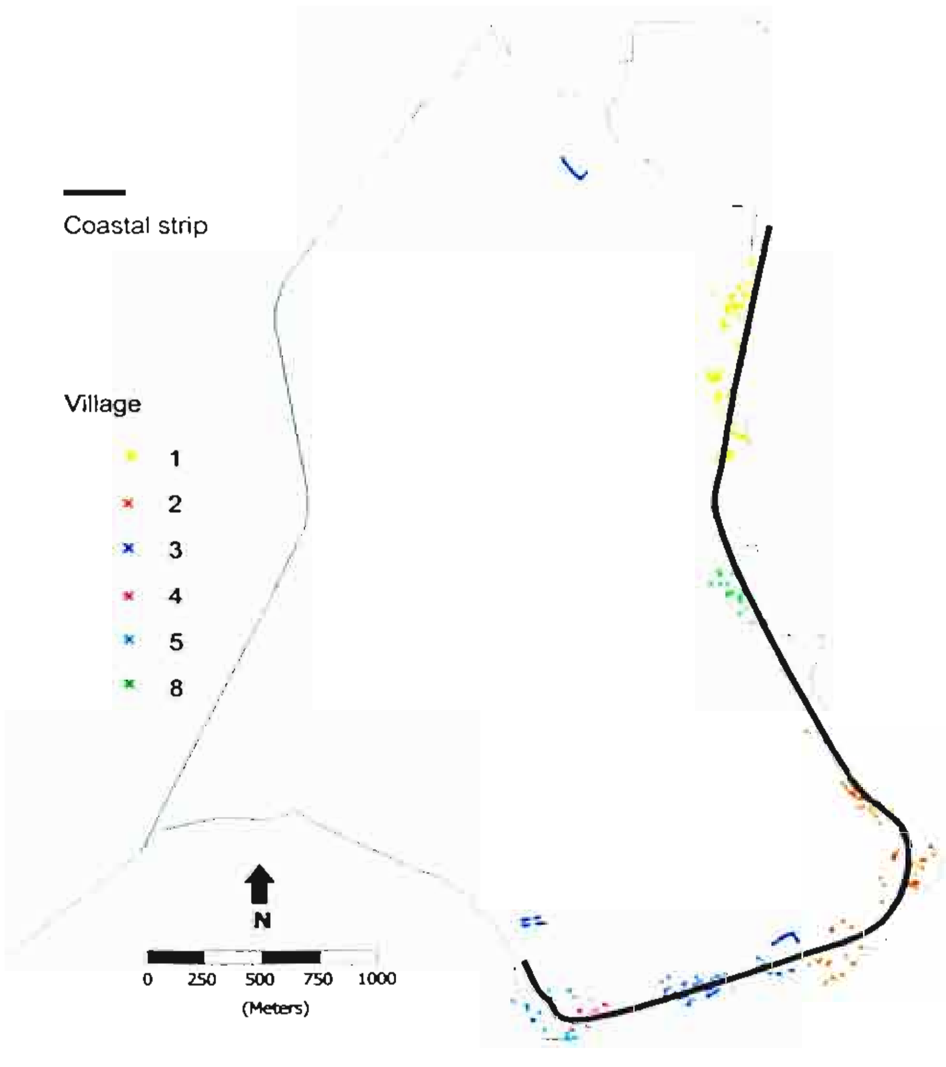


Figure 4.1 The coastal strip.

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.

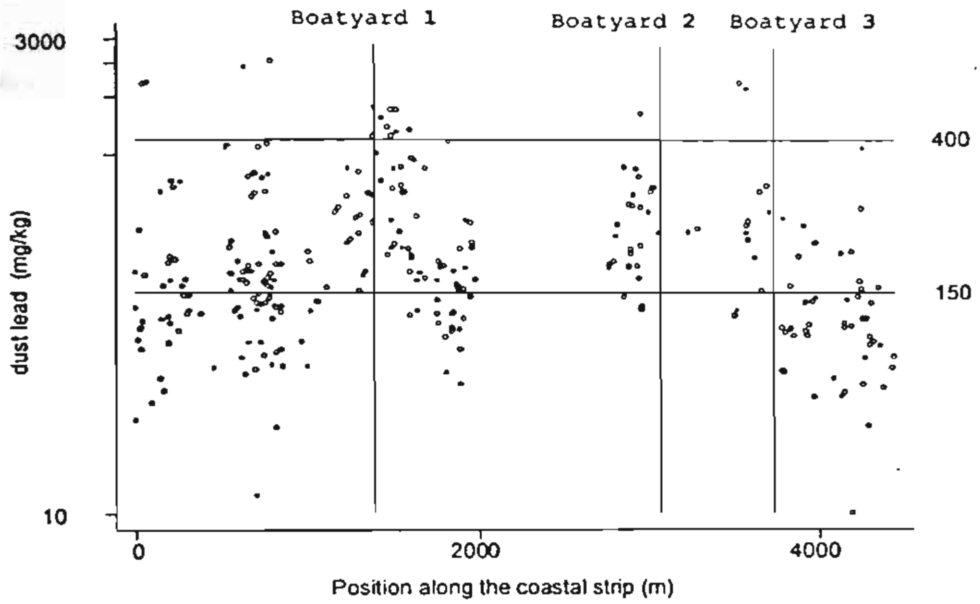


Figure 4.2 Distribution of household dust lead concentration along the coastal strip. Note the logarithmic y scale.

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.

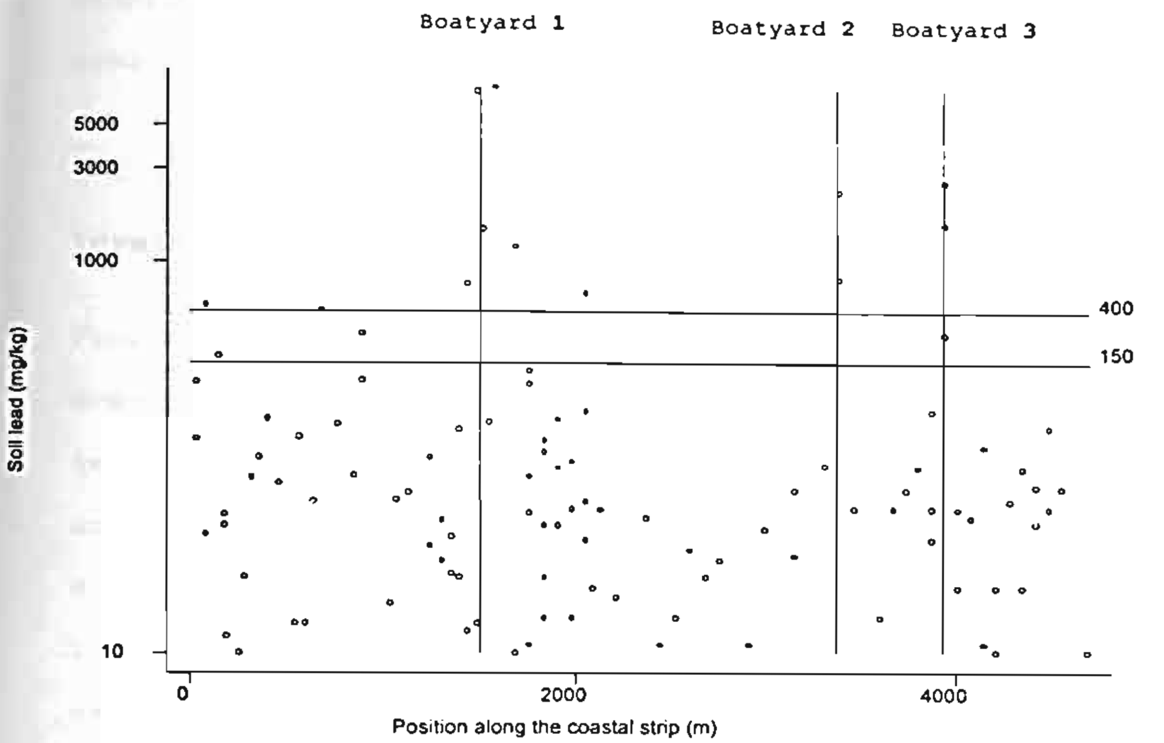


Figure 4.3 Distribution of soil lead concentration along the coastal strip. Note the logarithmic y scale.

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.

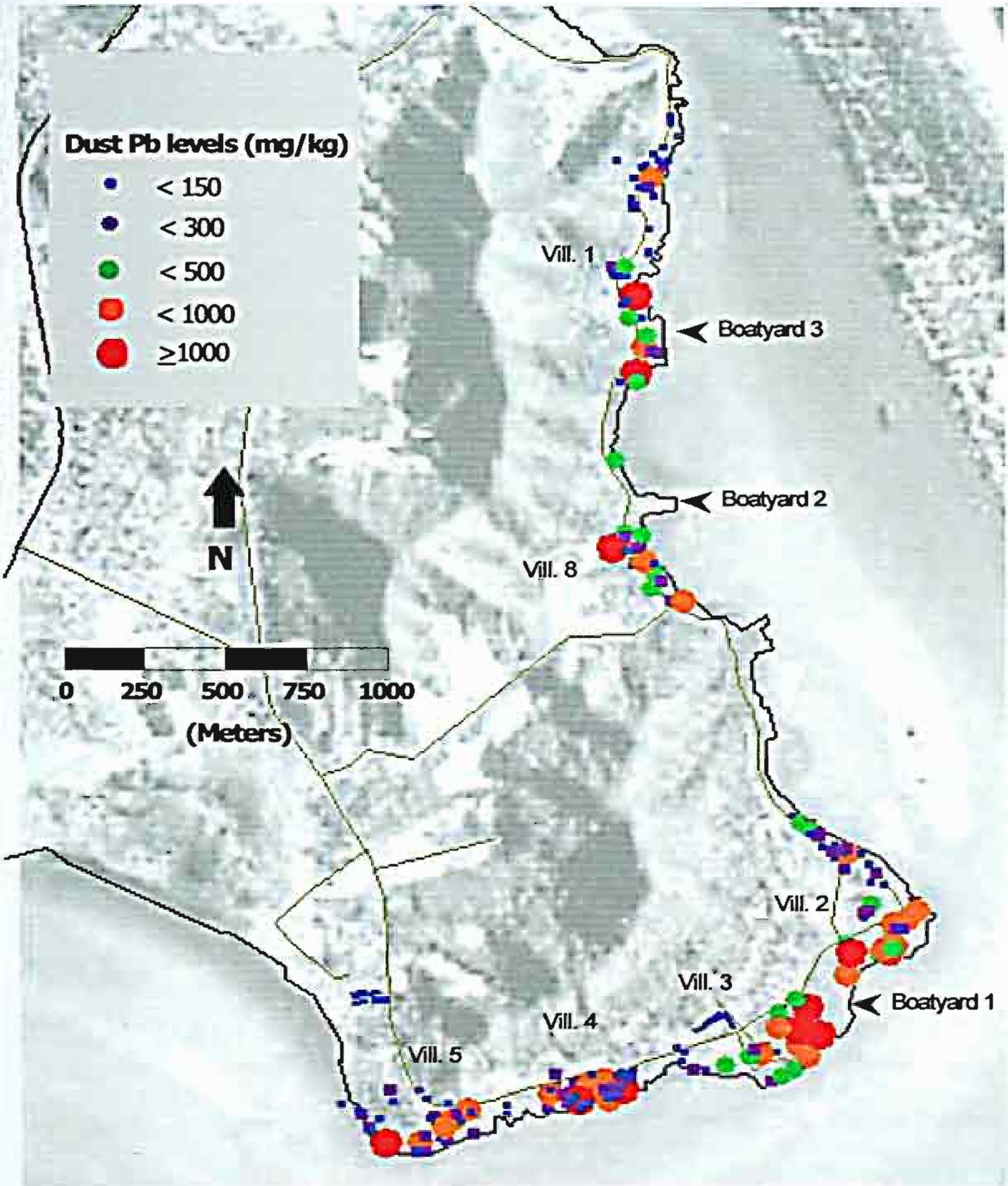


Figure 4.4 Spatial distribution of household dust lead levels superimposed on an aerial photograph of the study area.

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.

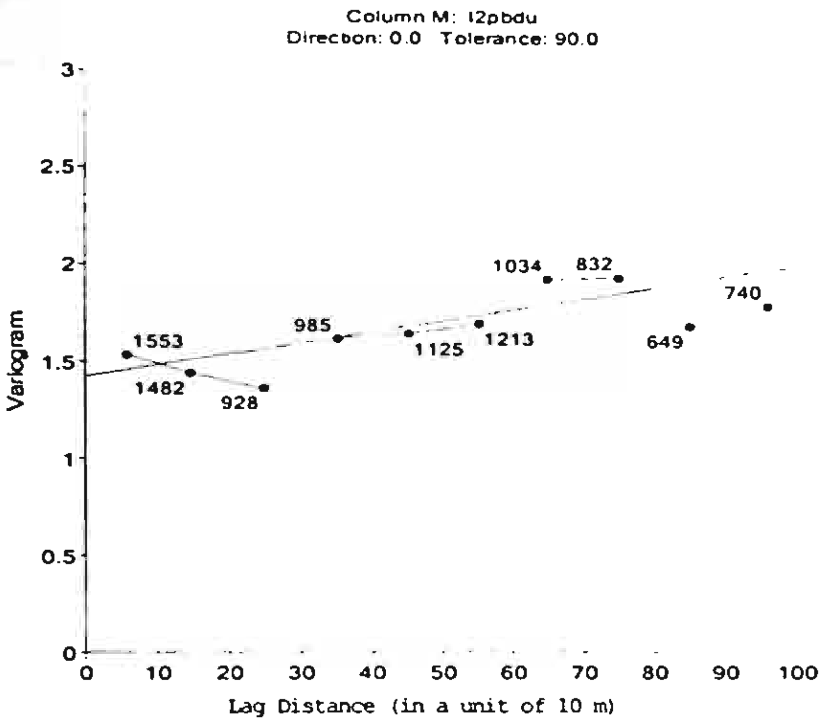


Figure 4.5 Omnidirectional variogram of household dust lead levels. (maximum lag distance 1300 m, lag width 100 m, nugget effect 1.493 and slope 0.00147).

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).

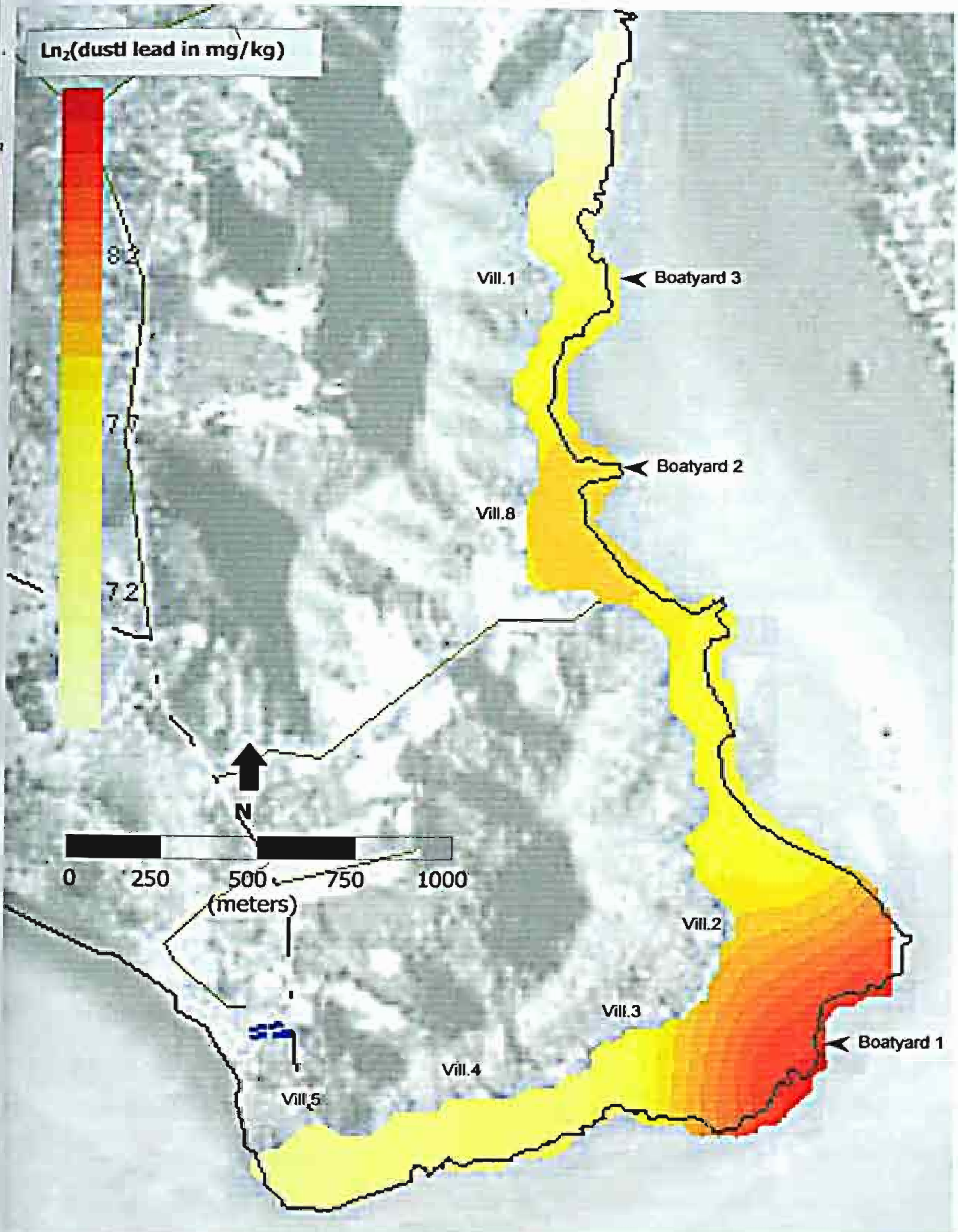


Figure 4.6 Contour map of household dust lead levels created using kriging.

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.

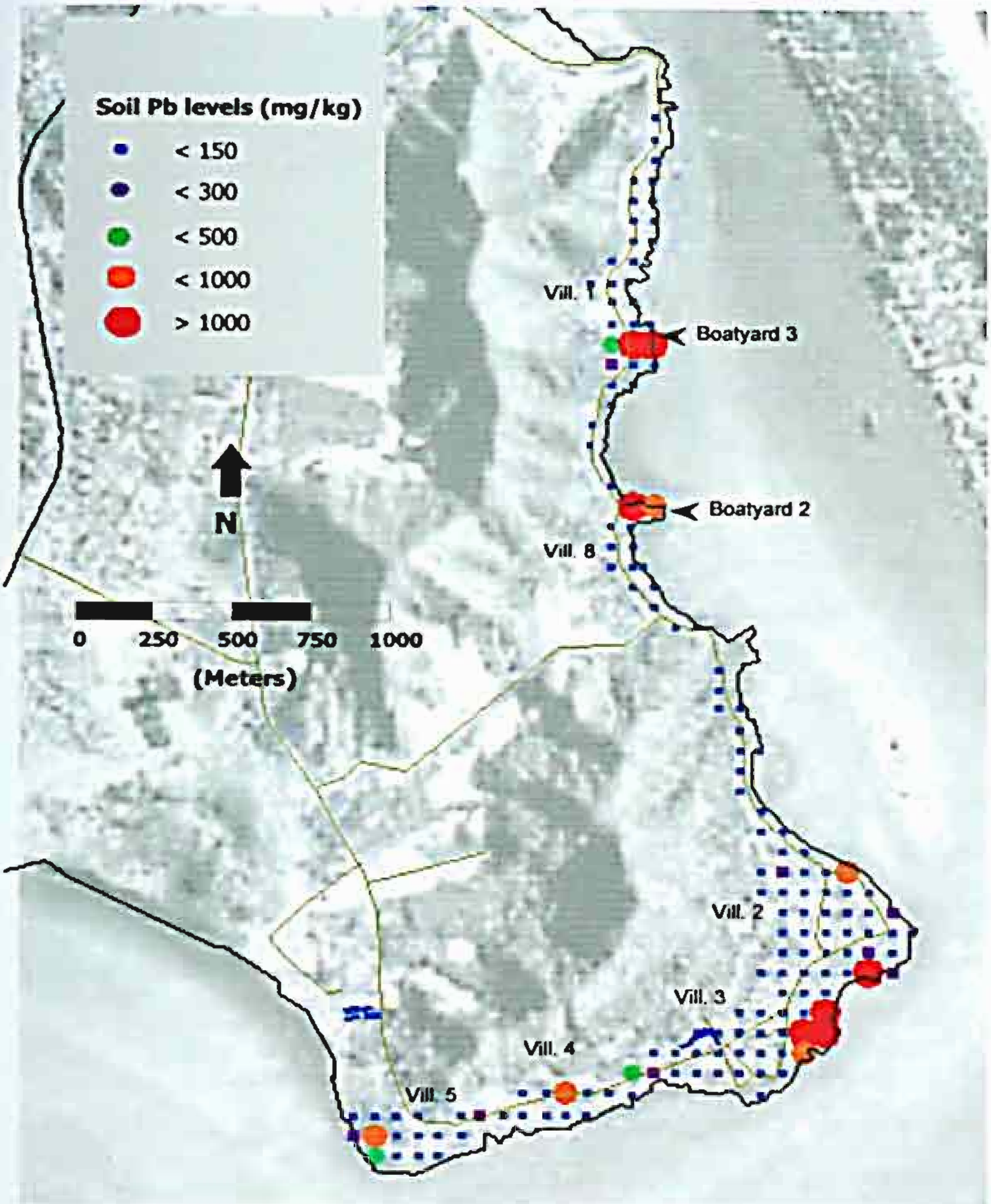


Figure 4.7 The distribution of soil lead at sampling points, superimposed on an aerial photograph of the study area.

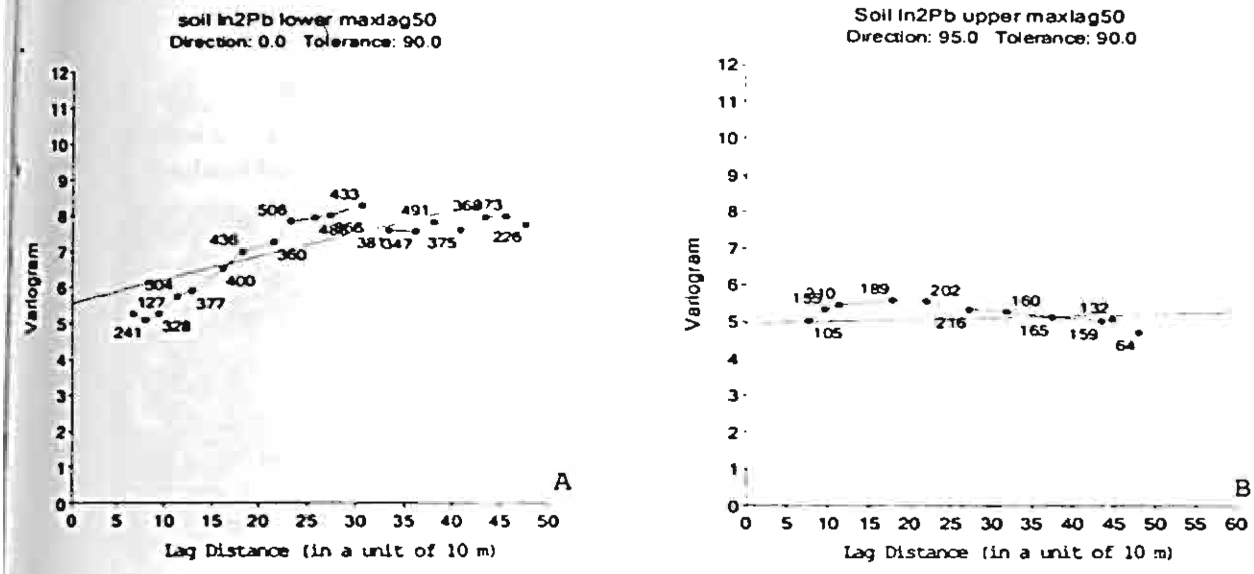


Figure 4.8 Omnidirectional variogram of soil lead levels. (A) Lower part of the study area (maximum lag distance 500 m, lag width 100 m, nugget effect 5.54 and slope 0.0418). (B) Upper part of the study area (maximum lag distance 500 m, lag width 100 m, nugget effect 4.95 and slope 0.0029).

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.