

# **Artisanal Gold Mining, Mercury and Sediment in Central Kalimantan, Indonesia**

by  
Daniel Stapper  
B.Sc., University of Victoria, 2006

A Thesis Submitted in Partial Fulfillment of Requirements  
for the Degree of  
MASTER OF SCIENCE  
in the Department of Earth and Ocean Sciences

© Daniel Stapper, 2011  
University of Victoria

All rights reserved. This thesis may not be reproduced in whole or in part, by photocopy  
or other means, without the permission of the author.

## **Supervisory Committee**

Artisanal Gold Mining, Mercury and Sediment in Central Kalimantan, Indonesia

by

Daniel Stapper

B.Sc., University of Victoria, 2011

Supervisory Committee

Dr. Kevin Telmer, Department of Earth and Ocean Science

Supervisor

Dr. Eileen Vander Flier-Kellar, Department of Earth and Ocean Science

Departmental Member

Dr. Richard Hebda, Department of Earth and Ocean Science

Departmental Member

## Abstract

### Supervisory Committee

Dr. Kevin Telmer, Department of Earth and Ocean Science  
Supervisor

Dr. Eileen Vander Flier-Kellar, Department of Earth and Ocean Science  
Departmental Member

Dr. Richard Hebda, Department of Earth and Ocean Science  
Departmental Member

### Abstract

A field survey was undertaken in Central Kalimantan, Indonesia (Borneo) to assess the extent and practices of Artisanal and Small-scale Gold Mining (ASGM), and to measure sediment and mercury flows in the provinces' rivers. More than forty mining operations were visited in six of the provinces largest river basins during June, July and August of 2008. Based on the survey results, this thesis estimates that 43,000 small-scale gold miners in Central Kalimantan produced 13.3 tonnes of gold in 2008 (426,000 troy ounces - ozt) worth approximately 362 million CAD (based on 2008 international gold price of 850 CAD/ozt). Mercury use was ubiquitous for leaching gold from ores in the province. Approximately 65.3 tonnes was used for this purpose in 2008, with the majority of consumption- 80% by whole-ore amalgamation operations exploiting hard-rock deposits, but producing only 13% of the gold. These estimates have been interpolated using (i) measurements and detailed observations at more than forty ASGM operations surveyed in five different regencies; (ii) numerous interviews with

miners, gold shops owners and officials across these regencies; and (iii) mapping of ASGM operations using satellite imagery.

Hydraulic mining methods mobilize enormous volumes of sediment and native sediment-bound mercury. Sediment and mercury fluxes associated with ASGM activities were estimated based on a river sediment sampling campaign carried out in conjunction with the ASGM survey, and on subsequent modelling of river sediment transport. On streams and tributaries, mining activities increased sediment transport by factors between 100 and 1500, resulting in a net doubling of sediment loads on large first order river channels, on which the effects of mining are diluted in space and time by channels without mining. Particulate mercury flux sampled on six of Central Kalimantan's largest river channels averaged 60ng/L  $\pm$ 33%, a high figure relative to most global rivers, despite average suspended sediment concentrations of only 75mg/L  $\pm$ 58%. Based on a hydrological and sediment transport model, 19.4 tonnes of mercury ( $\pm$ 30%) transits these river systems annually, dominantly transported as suspended sediment load (95%), with the remaining 5% transported as bedload.

Acute mercury exposure by inhalation during the burning of mercury-gold amalgam represents an important health concern at ASGM camps and gold shops. In relation to mercury, sector improvements should focus on eradicating whole ore amalgamation, and open burning of amalgam. Eliminating whole ore amalgamation requires technological improvements at the gold liberation (crushing and milling) and concentration stages of ore processing. Elimination of open-air burning can be achieved through education, and the use of retorts, fumehoods, and mercury re-activation cells—each of these basic technologies provide mercury users with economic incentives by reducing mercury consumption.

## Table of Contents

<b>Supervisory Committee .....</b>	<b>ii</b>
<b>Abstract .....</b>	<b>iii</b>
<b>Table of Contents.....</b>	<b>v</b>
<b>List of Tables.....</b>	<b>ix</b>
<b>List of Figures.....</b>	<b>x</b>
<b>List of Photography Panels.....</b>	<b>xi</b>
<b>Acknowledgments .....</b>	<b>xiv</b>
<b>Chapter 1. Background.....</b>	<b>1</b>
1.1 Introduction .....	1
1.1.1 Overview .....	1
1.1.2 Layout.....	1
1.1.3 Study Approach.....	2
1.2 Background Material .....	3
1.2.1 ASGM in Central Kalimantan .....	3
1.2.2 Use of Mercury in gold and silver mining .....	3
1.2.3 Gold Extraction with Cyanide .....	5
1.2.4 ASGM and Sediments .....	6
1.2.5 Elemental Mercury .....	7
1.2.6 Mercury Geochemistry .....	8
1.2.7 Mercury and Health .....	10
1.2.8 Methyl-mercury .....	12
1.2.9 Biomagnification and Toxicity.....	14
1.2.10 Research on ASGM and Mercury in the Tropics .....	15
1.3 Study Area.....	16
1.3.1 Physical Geography of Central Kalimantan.....	16
1.3.2 Administrative Setting .....	19

1.3.3	Land Use.....	21
1.3.4	Geology of Borneo .....	21
1.3.5	Gold Deposits of Central Kalimantan.....	23
1.4	Erosion and Sediment Transport in Borneo .....	26
1.4.1	Sediment Removal .....	26
1.4.2	Measurement of Sediment Transport .....	26
1.5	Mercury fluxes in Central Kalimantan .....	28
1.5.1	Deposition, Sequestration and Volatilization .....	28
1.5.2	Weathering of rocks.....	31
1.5.3	Sources of streamflow mercury.....	31
1.5.4	Dissolved phase Hg stream flow .....	31
1.5.5	Particulate phase Hg stream flow.....	32
1.5.6	Dissolved Organic Matter .....	32
<b>Chapter 2. Artisanal and Small-scale Gold Mining in Central Kalimantan, Indonesia ...</b>		<b>34</b>
2.1	Introduction .....	34
2.1.1	Chapter preface .....	34
2.1.2	History of ASGM in Indonesia .....	34
2.1.3	Legal status of ASGM in Central Kalimantan .....	35
2.2	Survey Methods .....	36
2.2.1	Language and institutional support .....	36
2.2.2	Satellite imagery .....	36
2.2.3	Travel and engagement with gold mining communities .....	36
2.3	Results of Survey.....	37
2.3.1	ASGM labor force.....	37
2.3.2	Classification of ASGM operations.....	38
2.3.3	Buried placers .....	39
2.3.4	Alluvial placers .....	61
2.3.5	Hydrothermal lode gold.....	71
2.3.6	Estimates of mercury use and fate in Central Kalimantan .....	80
2.3.7	Total mercury emissions from ASGM in Central Kalimantan .....	84

2.3.8	Assessment of the ASGM gold sector in Central Kalimantan .....	84
2.4	Chapter summary .....	86
<b>Chapter 3.</b>	<b>River Sediment Study .....</b>	<b>87</b>
3.1	Introduction .....	87
3.2	Methods .....	87
3.2.1	River water and sediment sampling .....	87
3.2.2	Bedload sediment sampling.....	89
3.2.3	Suspended sediment sampling for total suspended solids (TSS) .....	89
3.2.4	Startigraphic profile sediment samples .....	90
3.2.5	Grain size.....	90
3.2.6	Organic matter .....	90
3.2.7	Mercury Analysis.....	90
3.2.8	Error in TSS and mercury analysis.....	91
3.2.9	X-Ray diffraction .....	91
3.2.10	Gold analysis by fire assay .....	92
3.3	Results and discussion .....	93
3.3.1	Mercury concentration of native sediments .....	93
3.3.2	Bedload sediments.....	93
3.3.3	Suspended sediments .....	96
3.3.4	Suspended sediments near mining activities .....	100
3.3.5	Suspended sediments in main river channels .....	103
3.3.6	Suspended sediments during high water flows (storm surges) .....	105
3.3.7	Variability of mercury in sediments.....	106
3.3.8	Organic sediments .....	106
3.3.9	XRD Results .....	107
3.4	Modeling sediment and mercury flux.....	108
3.4.1	Introduction .....	108
3.4.2	Methods .....	109
3.4.3	Runoff Coefficient .....	110
3.4.4	River discharge estimates .....	111

3.4.5	Suspended Sediment Transport .....	112
3.4.6	Sediment Rating Curve .....	112
3.4.7	Flow Duration.....	114
3.4.8	Bed Material Transport.....	117
3.4.9	Bedload Sediment Transport Formulae.....	118
3.4.10	Total sediment and mercury flux estimates .....	122
3.4.11	Flux estimate uncertainty .....	123
3.5	Chapter summary .....	123
<b>Chapter 4. Improving the ASGM Sector.....</b>		<b>126</b>
4.1	Development of the ASGM Sector.....	126
4.2	Improving how mercury is used in Central Kalimantan.....	127
4.2.1	Retorts.....	127
4.2.2	Water-trap condenser for use with fumehood .....	130
4.2.3	Mercury Re-activation .....	131
4.3	Improving the concentration stage of ore processing .....	132
4.4	Alternative leaching technologies .....	133
4.5	Reducing sedimentation and improving mine site management .....	133
4.6	Formalization and enforcement .....	135
4.7	Chapter summary .....	135
<b>Bibliography .....</b>		<b>136</b>

## List of Tables

Table 1. Estimates of mercury evasion from Peat fires in Kalimantan.....	30
Table 2. Suspended sediment statistics.....	97
Table 3 Suspended sediment sample variability. ....	100
Table 4. Mercury measurments from streams and tributaries affected by mining. ....	102
Table 5. Mass Balance for TSS and mercury based on average conditions.....	112
Table 6. Annual sediment flux of the Kahayan River .....	116
Table 7. Annual sediment and mercury flux estimates for all sampled rivers .....	117
Table 8. Bedload sediment and mercury flux. ....	118
Table 9. Sample Input for Bedload transport formulae.....	120
Table 10. Bedload transport formulae results for Kahayan River at Palangkaraya.....	121
Table 11. Bedload sediment transport predictions. ....	121
Table 12. Total sediment and mercury flux estimates .....	122

## List of Figures

Figure 1. Classius Clayperon behaviour of mercury .....	7
Figure 2. Global biogeochemical mercury cycle .....	10
Figure 3. Dominant mercury transformation pathways.....	13
Figure 4. Map of Indonesia .....	17
Figure 5. River basins of Central Kalimantan .....	18
Figure 6. Map of Central Kalimantan’s administrative regencies and cities .....	20
Figure 7. Geology of of Central Kalimantan.....	22
Figure 8. Map of Survey Route. ....	37
Figure 9. Map of river sampling locations. ....	88
Figure 10. Grain size analysis and mercury concentration of bedload samples. ....	94
Figure 11. Mercury concentration and flux of high TSS water samples.....	98
Figure 12. Mercury concentration and flux of low TSS water samples .....	98
Figure 13. TSS sample trends for high TSS water samples .....	99
Figure 14. TSS sample trends for low TSS water samples. ....	99
Figure 15. Correlation between stream TSS and mercury flux near mining activities. ...	101
Figure 16. Main channel TSS statistics.....	104
Figure 17. Correlation between TSS and mercury flux, main channels.....	104
Figure 18. (%TOC) verses mercury content for bedload sediment. ....	107
Figure 19. Hydrographic discharge measurements from the Berau River .....	111
Figure 20. Sediment Rating Curve for the Kahayan River.....	113
Figure 21. Generalized sediment rating curves. ....	114
Figure 22. Flow Duration curves for the Berau River, and the Kahayan River. ....	115

## List of Photography Panels

Photo Panel 1. Aerial views of the Galangan mine fields .....	41
Photo Panel 2. Large sluice boxes are used to concentrate pit sediments in Galangan..	43
Photo Panel 3. Miners work in pits to liberate sediments using water jets.....	43
Photo Panel 4. Miners beginning new pits in Galangan. ....	45
Photo Panel 5. Panoramic of a large pit being worked by four sluices in Galangan. ....	46
Photo Panel 6. Overburden sediments (tailings) from previous workings.....	47
Photo Panel 7. Aerial photograph of mine pits filled with water.....	48
Photo Panel 8. SPOT satellite image depicting pit management problem. ....	48
Photo Panel 9. Mercury used for Amalgamation in Galangan. ....	49
Photo Panel 10. Filtering mercury to recover amalgam; Galangan.....	50
Photo Panel 11. Amalgam sold to gold shops in Kereng Pangsi .....	51
Photo Panel 12. Mine real-estate near Pojon.....	53
Photo Panel 13. Sluice boxes are used for primary concentration near Pojon.....	54
Photo Panel 14. (left) Miners working in pit near Pojon .....	54
Photo Panel 15. Carpets are collected and washed to recover concentrate. ....	54
Photo Panel 16. Mercury used in Pojon .....	55
Photo Panel 17. Amalgamate around Pojon.....	55
Photo Panel 18. Pregnant mercury filtered using the miners t-shirt; Pojon .....	56
Photo Panel 19. Amalgam heated at gold shop in Pojon. ....	56
Photo Panel 20. Detrital platinum collected by miners around Pojon.....	57
Photo Panel 21. Miners working in pit near Tangar .....	57
Photo Panel 22. Miners working in a wetland area near Tangar .....	58
Photo Panel 23. Burning amalgam near Tangar .....	59
Photo Panel 24. Pit operations being worked in the upper Kahayan Basin .....	60
Photo Panel 25. Sluice carpets washed at the end of the day near Ponyoi .....	60
Photo Panel 26. Miners use water jets to dig pits in the Hamputung River basin.....	61

Photo Panel 27. Cutting trees to make space for dredges on the Kalanaman River. ....	62
Photo Panel 28. Teams of miners work together to mine clay rich river banks .....	63
Photo Panel 29. Sediment is pumped to the top of the dredge sluice box.....	63
Photo Panel 30. Pristine stream conditions in the Kapuas River.....	64
Photo Panel 31. River mining operations and sedimentation on the Muro River .....	64
Photo Panel 32. Sedimentation of small tributaries of the Kapuas River. ....	65
Photo Panel 33. Dredges rafted to one another in the Kapuas river .....	65
Photo Panel 34. A mine site along the Kahayan River channel. ....	66
Photo Panel 35 Stream shallows upstream of Ponyoi.....	67
Photo Panel 36. Miners operate small floating sluice boxes in stream channels. ....	67
Photo Panel 37. Sediment mobilization in headwaters of the Kahayan River .....	68
Photo Panel 38. Large dredges on the Barito River .....	69
Photo Panel 39. A team of miners work together on large Barito River dredges .....	70
Photo Panel 40. Wooden pulley wheels used lift the suction apparatus.....	70
Photo Panel 41. A large converted automobile engine is used to pump sediments .....	71
Photo Panel 42. Abandoned Gunung Baru LSM mine site (Kerekil veins, Mount Muro). 72	
Photo Panel 43. Miners descend into the open shaft for a five hour shift .....	73
Photo Panel 44. Ore brought to the surface is hammered into small pieces .....	73
Photo Panel 45. Large sheds in the village of Mangkuhoi contain trammel-mill circuits 74	
Photo Panel 46. Trammel mills are cleaned to recover mercury. ....	74
Photo Panel 47. Bowls of mercury are filled and the mercury is filtered.....	75
Photo Panel 48. Large fist size ball of amalgam and doré. ....	76
Photo Panel 49. Molten alloy is poured into water.....	77
Photo Panel 50. Alloy gravel is boiled in nitric acid .....	78
Photo Panel 51. Gold is dried and smelted again. ....	78
Photo Panel 52. Tailings moved by truck to a nearby property for CIP treatment.....	80
Photo Panel 53. One of ten 30,000 litre tongs used for CIP .....	80

Photo Panel 54. Stainless steel <i>Fauzi</i> retort .....	128
Photo Panel 55. Large retorts used for burning 10-20kg of mercury.....	129
Photo Panel 56. Water trap mercury capture add-on for wooden fumehoods.....	130
Photo Panel 57. ASGM pits are refilled with sediments in the Brazilian Amazon.....	134

## Acknowledgments

First I would like to acknowledge Kevin Telmer, my thesis supervisor. Kevin encouraged me to travel to Indonesia to study small-scale gold mining there. His guidance and advice contributed hugely to the success of my survey in Central Kalimantan. I would also like to thank friends and acquaintances I made in Indonesia, including numerous miners. Their help provided me with incredible education, and contributed instrumentally to this thesis. Specifically I thank Adam, Dina, Bardolf, Sumali, Lita, Mansur, Vita, Indra, Mayang, Asmi, Pak Henry, and Pak Fauzi.

I would like to acknowledge and thank my friends and family for their support and encouragement. My partner and confidant Carly helped me constantly throughout, providing relentless support, demonstrating compassion and patience the entire time. My mom and dad also provided invaluable encouragement.

I hope the thesis is read by many, and that the compilation of information is useful for inspiring and/or informing improvements in the ASGM sector in Indonesia, and elsewhere.

# Chapter 1. Background

## 1.1 Introduction

### 1.1.1 Overview

This thesis describes Artisanal Small-scale Gold Mining (ASGM) in Central Kalimantan, Indonesia and estimates mercury emissions from the sector. In addition, a river sediment survey is used to determine the effect of mining on sediment transport in the provinces' rivers.

The field survey was undertaken in 2008 to explore the extent and manner in which small-scale gold miners operate in Central Kalimantan. More than forty mining operations were visited, across seven of the province's fourteen districts, with mercury and sediments as principal research foci. The main goals of this study were to: (1) document the extent and practices of small-scale gold mining and mercury use; (2) measure the fluxes of sediment and mercury in the province's rivers; (3) determine the contribution of small-scale mining to these fluxes. From the outset this study was intended to support the broader, long-term goal of bringing sustainable development to ASGM communities.

### 1.1.2 Layout

Chapter one provides an introduction to the thesis and its main themes by reviewing relevant mercury processes, and introducing the geography and geology of the study area. In chapter two the field survey of ASGM operations made in June-August of 2008 is presented. At the end of this chapter survey data is used to estimate the amount of gold produced, the amount of mercury used and emitted, and the size of the ASGM sector in terms of population and gross regional domestic product (GRDP). Chapter 3 comprises a study of river sediments and mercury. Data from the sediment sampling campaign is presented, followed by analysis and discussion. Hydrological modelling is used to estimate sediment and mercury fluxes, and to determine the impacts of mining

on sediment and mercury transport. In Chapter 4, a cursory overview of potential sector improvements is made, focused mainly on how mercury is used, with specific examples from Central Kalimantan.

### **1.1.3 Study Approach**

A fieldtrip to Indonesia was conducted in June, July and August of 2008 to explore the extent and assess practices of ASGM in Central Kalimantan. During the survey, observations and measurements focused principally on sediment and mercury around mining operations. The field program had to remain flexible because the area is extremely remote and therefore logistical issues including communication, transport, and relations with individuals in mining communities and regional authorities, were not possible to predict. During the survey more than 40 mining operations were visited across five of the seven largest river basins in the province.

River water and sediments were sampled at 31 different locations, along with in situ measurements of suspended sediments (TSS), pH, and alkalinity. A range of channel sizes both near and distant from mining were sampled to determine the effects of ASGM across a range of spatial scales. Suspended and bedload sediments were collected for laboratory analysis of grain size and mercury. These data have been used to estimate fluxes of sediment and mercury in the province, and the contribution of ASGM to these fluxes.

The data-set produced for this thesis is unique in several aspects: it represents an interdisciplinary blend of sciences: geological, environmental and socio-economic; the analysis encompasses a wide range of scales: from mine sites to very large rivers; a photographic record of mining operations visited was made, some of which is included in the body of the thesis; apart from work on peat swamps, no information on Central Kalimantan's river systems has been published to date, and finally; little information on ASGM in Central Kalimantan was widely available, and this remains true for a majority of regions around the world with large, informal ASGM sectors (*informal* refers to illegal or partly legal elements of the sector, from mining permit holders to gold exporters).

## **1.2 Background Material**

### **1.2.1 ASGM in Central Kalimantan**

ASGM and the gold economy it supports in Central Kalimantan provide vital livelihoods for a significant proportion of the provinces two million inhabitants. For many it is a subsistence livelihood. As in many other countries, small-scale gold mining operations in Central Kalimantan are setup with limited capital investment. Self-organized economies of gold miners, gold shops, refiners, merchants, local artisans, and transporters create and distribute wealth in the ASGM sector. Over the past decade (2000-2010) the increase in the gold price (\$300CAD per troy ounce in 2000 to \$1200CAD per ounce in 2010) has enabled profitable mining of lower grade deposits, resulting in massive growth of the ASGM sector in numerous countries. It is widely accepted that between 5 and 10 million individuals in more than 70 countries are *directly* employed by ASGM activities; this number is growing and could be larger.

In Indonesia small-scale mining operates both legally, illegally, and sometimes in between – as in situations where miners work with permits for zircon mining but also mine gold. Mining practices vary depending on the type of ore being exploited. Laws which pertain to ASGM exist, but enforcement approaches and mechanisms are often ineffective. For example, mercury use for mining was illegal in the province in 2008, but despite this its' use as a primary gold recovery method was ubiquitous.

### **1.2.2 Use of Mercury in gold and silver mining**

The use of liquid mercury to extract gold from sediments is fast and cheap, and works well on most ore types if the gold is liberated. The earliest records of mercury use in alchemy and amalgamation are from Egypt and China more than 3000 years ago (Hylander and Meili 2003). The origin of the word amalgam is from Medieval Latin *amalgama*, meaning alloy of mercury with gold or silver. According to Hylander and Meili (2003), approximately one million tonnes of mercury have been extracted from cinnabar and other ores during the last five hundred years, and roughly half of this has been used for extracting gold and silver. During the same period the global atmospheric

mercury pool has roughly tripled (Mason, Fitzgerald et al. 1994). The largest anthropogenic mercury sources contributing to this increase have and continue to be coal burning (by-product mercury emissions) and gold and silver mining (demand-for-use mercury emissions).

Mercury is a liquid metal at standard conditions for temperature and pressure. Its' low freezing point (solidifies at  $-38.8^{\circ}\text{C}$ ) is attributed to a paired 6-s electron sub-shell, whose stability is reinforced by 4-f sub-shell electrons (Levlin, Niemi et al. 1996). The atomic mechanisms of mercury-gold amalgam remain only loosely understood, despite sophisticated experiments used to study them (Levlin, Niemi et al. 1996); (Kobiela, Nowakowski et al. 2003). Electron-shell interactions between mercury and gold produce metallic bonds between the metals which cause partial solidification of the mercury matrix with the inclusion of gold particles. Mass and density facilitate amalgamation as mercury ( $13.53\text{g}/\text{cm}^3$ ;  $200.59\text{g}/\text{mol}$ ) sinks below gangue minerals where it mixes with and adheres to gold particles ( $19.30\text{g}/\text{cm}^3$ ;  $196.97\text{g}/\text{mol}$ ). The solubility of gold in mercury at ambient temperature ( $25^{\circ}\text{C}$ ) is only 0.140 mole percent (0.138 mass percent, or 0.096 volume percent) (Guminski, Galus et al. 1986).

Mercury is typically brought into contact with a heavy mineral concentrate containing gold in a miners' gold-pan, bucket, sluice box, or trammel, where the silver coloured liquid metal amalgamates gold particles. The "pregnant" mercury is carefully retrieved and then filtered to remove liquid mercury that is not participating in the amalgam. What is left behind the cloth filter is a soft mixture of mercury and gold – an amalgam ball, which can be squeezed to remove excess liquid mercury. Afterwards, this amalgam is heated to remove mercury by volatilization. This is done using a blow torch, gas burner or coals from a fire. When heated, the mercury vaporizes leaving behind sponge gold – so named for its vesicular texture which results from the evacuation of mercury.

ASGM sites and gold shops where amalgam is heated represent mercury emission sources which warrant special attention at the community level. When these sources are considered collectively, they constitute a mercury emission source important at

regional and even global scales. In 2008, approximately 1000 tons of mercury was used and released to the global environment by ASGM (Telmer and Veiga 2009). ASGM is the largest direct-use source of mercury emissions on earth.

### **1.2.3 Gold Extraction with Cyanide**

Cyanide is widely used for processing gold and silver ores in both the LSM sector and the ASGM sector because of its propensity for dissolving these metals from ores. It is most commonly traded as a sodium-cyanide salt, which is dissolved in water when used. There are numerous cyanide methods used by small and large scale gold miners. A widely used method by small-scale operators observed in Central Kalimantan, is referred to as Carbon in Pulp (CIP). In this process, the gold bearing ore is mixed with water in a tank, and cyanide is added. Cyanide absorbs gold ions from the solution, forming aurocyanide compounds. Activated carbon (charcoal) is added to the mix, and acts like a sponge for aurocyanide  $[\text{Au}(\text{CN})_2^-]$  and other gold and silver ions in solution. After a period of agitation lasting 2-7 days, the carbon is collected and processed to recover gold and silver.

Cyanide is a poisonous compound principally due to its' propensity for oxygen. Its' use in mining and other industrial activities is especially hazardous because toxic hydrogen cyanide gas (HCN) is produced by cyanide solutions at ambient temperature (boils at 26°C), at circum-neutral pH. For this reason cyanide solutions must be kept alkaline. At pH 9.4 HCN and  $\text{CN}^-$  exist in equal amounts; at pH 11 more than 99% is  $\text{CN}^-$  (remains in solution); at pH 7, 99% of cyanide is HCN (deadly gassing).

Cyanide is of particular relevance to the study of ASGM and mercury because cyanide is sometimes used concurrently with mercury, which results in the possibility of cyanide complexes being formed with mercury. Where tailings or mercury-rich ores are processed with cyanide, effluent (tailings) from these operations is likely to contain toxic cyano-mercury complexes which can be transported in aqueous solution. Little is known about the behaviour, fate and bio-availability of cyano-mercury complexes. This is an important subject for future research, especially around ASGM operations.

#### **1.2.4 ASGM and Sediments**

Sedimentation and siltation of river systems, and a lack of mine site management or land reclamation practices are common problems in ASGM. These issues typically co-exist because mine areas including tailings piles which have not been remediated act as sediment sources even after mining activities cease. Abandoned mining areas are typically slow to re-vegetate because topsoil has been removed, topography has been altered, and natural sediment barriers have been altered or removed.

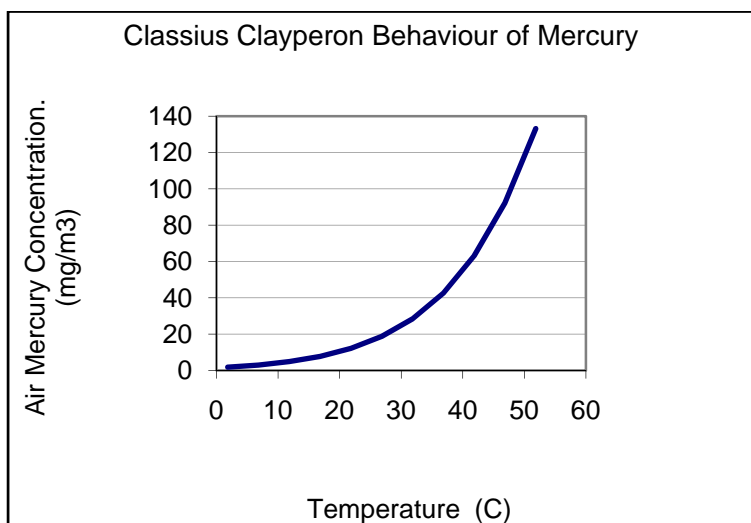
Sediments mobilized by ASGM have far-reaching effects on river ecosystems. In river basins where mining causes siltation, water chemistry and photic properties can be drastically altered (Mol and Ouboter 2004). Low energy river-reaches become depositional zones due to sedimentation. The result can be channels clogged with sediments, partially damming channels and restricting river transport. In regions where human populations rely on rivers for drinking water, municipal water systems can be negatively affected. In Palangkaraya, the capital of Central Kalimantan, particulate in the Kahayan River regularly causes problems for the municipality's water purification corporation. Production and accumulation of sediment (tailings) contaminated with mercury further exacerbate these concerns. Mercury contaminated sediments have the potential to cause widespread ecosystem health issues if conditions enable formation of methyl-mercury compounds.

Considering the modern proliferation of ASGM in numerous countries of the tropics, and the unequivocal disturbance ASGM causes to river systems, it is worth noting that this issue has received very little attention, relative to other river basin issues and concerns. Two of the largest modern compilations of academic literature on anthropological interactions with river basins in the tropics, do not address the issue of ASGM-related river basin disturbance including but not limited to siltation (Bonell and Bruijnzeel, 2004) (Hall, 2000) (Nagle, 1999).

### 1.2.5 Elemental Mercury

With a freezing point of  $-38.8^{\circ}\text{C}$  and boiling point of  $356.7^{\circ}\text{C}$ , mercury has one of the broadest ranges for its' liquid state of any metal. The heavy, silver coloured d-block metal is one of five metallic elements that are liquid, near room temperature and pressure. Mercury is the densest known liquid, and is also denser than lead. Liquid elemental mercury ( $\text{Hg}^{2+}$ ) is produced from the mineral Cinnabar - mercury sulphide ( $\text{HgS}$ ), by heating the ore to evaporate and then condense the mercury.

Mercury has high vapor pressure which is strongly controlled by temperature. Its vapour pressure at  $25^{\circ}\text{C}$  is  $0.002\text{ mmHg}$  ( $0.267\text{ Pa}$ ;  $18\text{mg}/\text{m}^3$  at equilibrium), but rises to  $0.013\text{ mmHg}$  ( $1.73\text{ Pa}$ ;  $110\text{mg}/\text{m}^3$  at equilibrium) at  $50^{\circ}\text{C}$ . This relationship is represented by the Classius Clayperon behaviour of mercury concentration in equilibrium with air – see figure 1. The figure shows that the rate of volatilization increases dramatically with temperature.



**Figure 1. Classius Clayperon behaviour of mercury concentration in equilibrium with air.**

As a result, heating amalgam is very effective for evaporating mercury, but the procedure produces concentrated mercury vapours that can be inhaled and absorbed into the bloodstream via the lungs. This is the most acute health threat to miners and

gold shop operators who are often uneducated with respect to this exposure pathway. Mercury vapour is invisible and odourless.

The consequence of high vapour pressure is high rate of volatilization, even at standard temperature and pressure (a standard atmosphere at ambient temperature saturated with mercury contains between 10 and 20mg Hg/m<sup>3</sup> of air). The occupational limit for mercury vapour in Canada – the ceiling level which should never be exceeded in a work environment, is 0.1mg/m<sup>3</sup> (Canadian Centre for Occupational Health and Safety).

Mercury's surface tension of 480 dynes/cm (20°C) is among the highest of all known liquids. This characteristic contributes to the problem of mercury flouring, when mercury micro-droplets prevent coalescing of liquid mercury. Mercury flouring causes loss of mercury to tailings, causing reduction in gold recovery, and contamination of tailings. In addition to the force of surface tension, additional factors that contribute to flouring include oxide minerals which tend to coat surfaces of tiny mercury droplets, and charged water molecules which may also play a role in preventing coalescence of tiny mercury particles.

#### **1.2.6 Mercury Geochemistry**

Nearly all mercury in the atmosphere (98%) occurs as elemental mercury vapour (Hedgecock and Pirrone 2004). The remaining two percent consists of reactive gaseous mercury and particulate or aerosol associated mercury. Elemental mercury can be transported long distances in the atmosphere where its residence time can be several years (Schroeder and Munthe 1998). When atmospheric mercury becomes oxidized it is typically deposited within a matter of days depending on climatic events and conditions. Oxidizing sources in the atmosphere include ozone, water, aerosol particles, hydroxyls, and ions of chlorine and bromine (Hedgecock and Pirrone 2004).

Geologically, mercury is mainly associated with sulphides and oxides. Average mercury concentrations of continental crust are 40ppb (ng/g), with most rocks ranging between 10 and 200ppb (Smith, Kesler et al. 2008). Background mercury concentrations in tropic

soils and sediments reported by most researchers range between 50 and 300 ng/g (Roulet et al., 1998) (Grimaldi and Guedron 2008), but have also been reported as high as 800ng/g in ferrallitic soils of South America (Grimaldi et al., 2002). Sediment mercury is most commonly associated with sulphide, oxide minerals and generally has low solubility in ambient waters (Veiga, Hinton et al. 1999).

Mercury adsorption to mineral and organic surfaces is controlled predominantly by pH and dissolved ions (ionic strength). Increases in ion concentration and/or decreases in pH will decrease mercury adsorption to negatively charged ligands. Clay and organic soils have high capacity for adsorbing mercury due to large negatively charged surface areas, and high cation exchange capacities (Schuster, 1991) (Stein et al., 1996) (Peretyazhko et al., 2006) (do Valle et al., 2005).

The behavior of mercury in soil is mainly controlled by adsorption and desorption processes depending on complexation, with the most important ligands in solution being  $\text{OH}^-$ ,  $\text{Cl}^-$ , and organic anions. High solubility of  $\text{HgCl}_2$  and  $\text{Hg}(\text{OH})_2$ , relative to other mercury species, makes these forms important in most complexation reactions (Schuster, 1991). High affinity of mercury to sulphur explains the strong binding of mercury to soil organic matter, and the stability of mercury's native form,  $\text{HgS}$ . Thus,  $(\text{OH}^-)$ ,  $(\text{Cl}^-)$ , and  $(\text{S}^-)$  ions have the greatest influences on mercury ligand formation in the terrestrial environment. Under oxidized surface soil and sediment conditions,  $\text{Hg}(\text{OH})_2$ ,  $\text{HgCl}_2$ ,  $\text{HgOH}^+$ ,  $\text{HgS}$ , and  $\text{Hg}^0$  are the predominant inorganic forms of mercury. In reduced environments common mercury species include  $\text{HgSH}^+$ ,  $\text{HgOHSH}$ , and  $\text{HgClSH}$ . In natural systems, many of these mercury species are associated with more complex organic and inorganic ligand molecules (Mauro, Guimaraes et al. 2002).

Mercury can be concentrated in sediments by weathering reactions. In aqueous terrestrial and near shore sediments, higher levels of mercury are often measured from upper layers of sediment columns. While some authors have attributed these increases

to inputs from anthropogenic sources, the propensity of mercury to associate with iron and manganese oxides has also been implicated (Walsh, 1997)(Telmer et al., 2005).

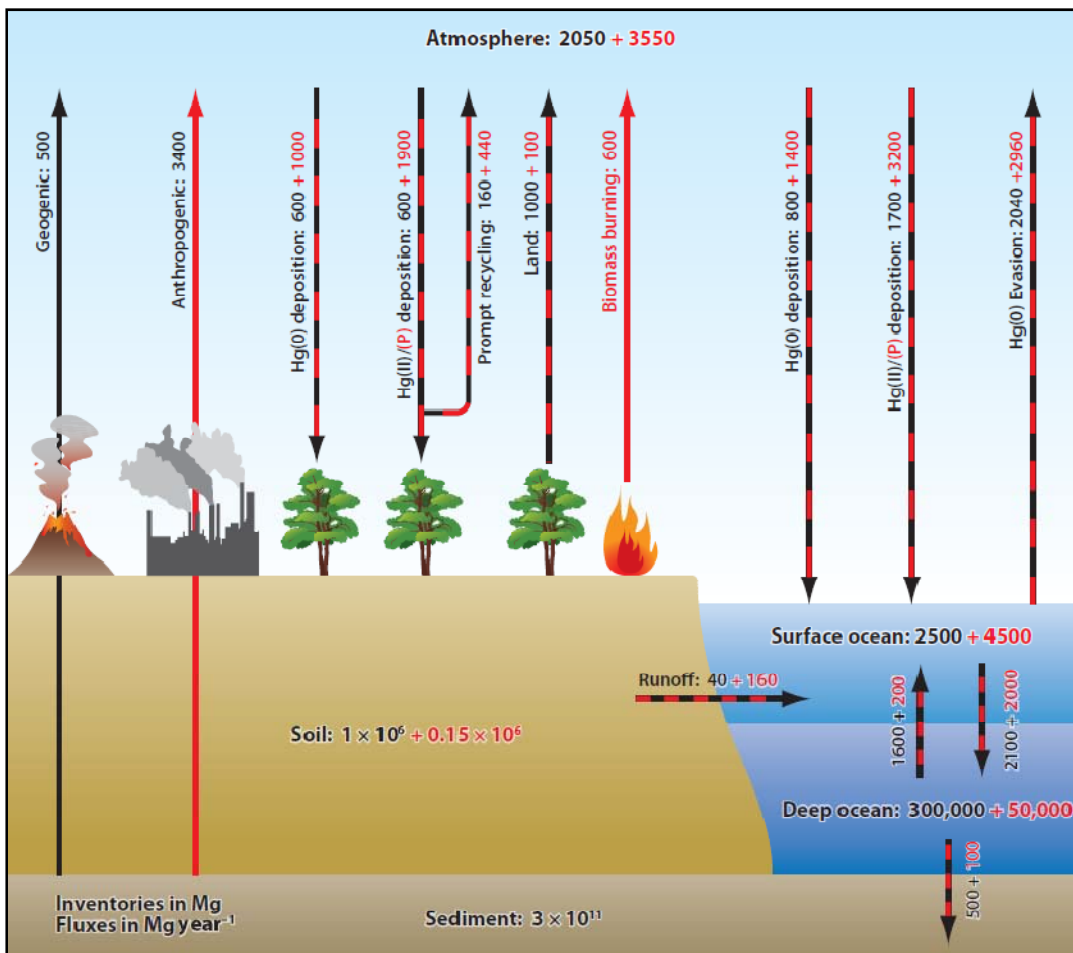


Figure 2. Global biogeochemical cycle for mercury, adapted from Selin et al (2009). Natural (pre-industrial) fluxes and inventories, in metric tonnes are noted in black. Anthropogenic contributions are in red. Natural fluxes augmented by anthropogenic activities are noted by red-and-black dotted lines.

### 1.2.7 Mercury and Health

Methyl-mercury is the most toxic form of mercury, and responsible for the majority of health concerns associated with the heavy metal. Modern medical understanding of mercury poisoning can be traced to the Japanese city of Minimata. From 1932 to 1968 methyl-mercury contaminated industrial wastewater from a chemical factory was discharged into Minimata Bay. The methyl-mercury accumulated in fish and shellfish

and poisoned thousands of fish-eating residents, eventually killing more than 1700 people. In 1956, when it was discovered that mercury was the source of the epidemic, mercury poisoning became widely known as Minimata Disease.

In the wake of this and other epidemics, progress was made in many countries from the 1970's through the 1990's to place controls on industrial mercury applications, to reduce its use, and to restrict emissions. Significant emission reductions were made by banning mercury based fungicides, controlling mercury-cell chlor-alkali plants, and recycling solid wastes (Hylander and Meili 2003).

For humans around the world the most prevalent exposure to mercury comes from eating contaminated fish and shellfish. The Foods Directorate of Health Canada has set the maximum recommended intake for total mercury of 0.5 parts per million (ppm) in domestically produced and imported fish. This guideline is enforced by the Canadian Food Inspection Agency. The directorate also advises that pregnant women, women of childbearing age, and young children should limit intake of methyl mercury to 0.2 microgram per kilogram of body weight per day. This equates to not more than one meal per month of predatory fish such as shark, swordfish and fresh or frozen tuna.

In the case of artisanal mining communities, acute exposures result from skin contact with mercury (generally the hands) and by inhalation of vapors near volatilization sources. Skin contact with elemental mercury is very common in ASGM but represents only minor exposure when compared with inhalation. Approximately 80% of inhaled mercury vapor is absorbed via the respiratory tract and then enters the circulatory system (George Cherian and Goyer 1978). Evidence based on animal subjects suggests that only a small proportion of elemental mercury (<1%) is absorbed through the intact gastrointestinal tract if ingested (Clarkson and Magos 2006).

Mercury is recognized as a toxin of global concern due to its persistence in the environment, its long-range transport in the atmosphere, its ability to bio-accumulate in ecosystems and organisms, and its negative effects on human health and the

environment. These characteristics, and increasing understanding of them by health officials and policy makers continues to spur legislative approaches to further reduce and control mercury emissions. Mercurys' residence time in the

The United Nations Environment Program has convened a group called the Global Mercury Partnership, responsible for drafting a globally binding instrument (treaty) on mercury which is being negotiated and plans to take force in 2013. As part of coordinated global efforts, the USA and EU have committed to discontinue trading from their mercury stockpiles. It is likely that these and other actions will force the international mercury price to increase. How the policy instrument will address consumption, demand and trade issues relating to ASGM mercury is being discussed by the Global Mercury Partnership and other parties involved in drafting the mercury treaty.

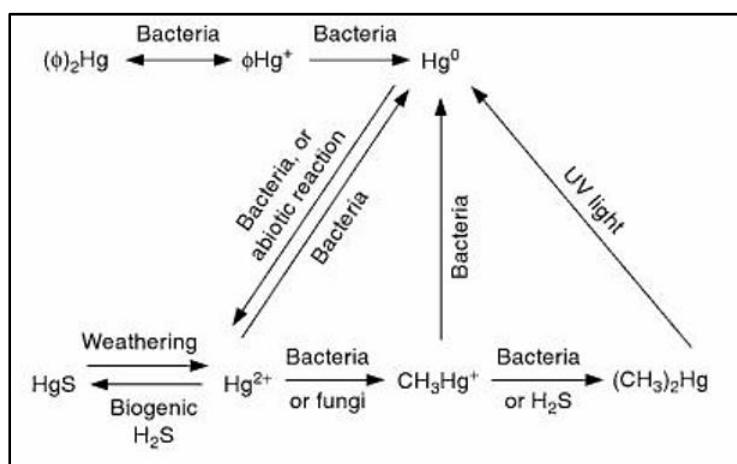
### **1.2.8 Methyl-mercury**

Methyl-mercury, also known as mono-methyl mercury, is formed when methyl groups ( $\text{CH}_3$ -) bind with oxidized mercury atoms ( $\text{Hg}^{2+}$ ). The result is an organic (methylated) mercury compound ( $\text{CH}_3\text{Hg}^+$ ) also written as  $\text{MeHg}^+$ . As a positively charged ion  $\text{MeHg}^+$  readily combines with anions such as chloride ( $\text{Cl}^-$ ), hydroxide ( $\text{OH}^-$ ) and nitrate ( $\text{NO}_3^-$ ) and has high affinity for sulfur-containing anions. As a result of its affinity for the sulfhydryl ( $-\text{SH}$ ) groups on the amino acid cysteine, covalent bonds can be formed attaching mercury to proteins containing cysteine (Ullrich, Tanton et al. 2001) (Govindaswamy, Moy et al. 1992). Inside mammalian bodies the methyl-mercuric-cysteinyll complex is recognized by amino-acid transporting proteins in the body as methionine, an essential amino acid and due to this mimicry it is transported freely throughout the body, including across the blood-brain and placental barriers – posing a grave health threat (Ullrich et al., 2001).

Methylation processes occur predominantly in aquatic systems and represent a critical component of the global mercury cycle, linking it with the carbon cycle and resulting in the elements most widely toxic forms. Relative to atmospheric mercury processes, this

linkage has not received a large amount of study. Understanding this linkage better will provide important insight regarding the global mercury cycle (MacDonald 2011). Recent research suggests that methylation reactions in pelagic (as oppose to benthic) food webs, may be of considerable importance in terms of marine methyl-mercury production (Sunderland and Mason 2007).

In recent decades large amounts of mercury research have focused on atmospheric deposition and transport, and on anoxic sediment boundaries and the benthic food web. A variety of microorganisms, particularly methanogenic and sulfate-reducing bacteria have been implicated in the conversion of  $\text{Hg}^{2+}$  to MeHg in anaerobic environments (Roulet, Guimaraes et al. 2001; Ullrich, Tanton et al. 2001; Mauro, Guimaraes et al. 2002); (Miranda, Guimaraes et al. 2004) (Coelho-Souza, Guimaraes et al. 2006). Several of the mechanisms and parameters which facilitate mercury methylation are only partly understood, but these are not discussed here.



**Figure 3. Dominant mercury transformation pathways by microbes, and chemical and physical agents. From Geo-microbiology (Ehrlich and Newman 2009).**

Regularly inundated riparian zones and wetlands of Central Kalimantan possess large amounts of DOM and submerged vegetation, characteristics which have been shown to increase mercury methylation potential. River fish are an important dietary source of protein in many parts of Central Kalimantan and many of the fish consumed come from local rivers and wetlands affected by mining. In light of this, study of mercury loads of predatory fish caught and consumed for Central Kalimantan's rivers is recommended to assess the level of risk for methyl-mercury ingestion by the population. This thesis does not include study or analysis of methyl-mercury.

### **1.2.9 Biomagnification and Toxicity**

Because methyl-mercury binds strongly to proteins it is not readily eliminated by organisms but accumulates and is bio-magnified in aquatic food chains from bacteria to plankton, through macro-invertebrates to herbivorous fish and then piscivorous fish. At each level of the food web methyl-mercury concentration increases (bio-magnification). Organisms which feed on piscivorous fish including predatory fish, sea birds, sea mammals and humans ingest the largest amounts of methyl-mercury accumulated by this process and are at highest risk of toxic exposure levels.

Mercury poisoning symptoms exhibited by humans depend upon the form and duration of mercury exposure (Clifton and Jack 2007). Symptoms can include sensory impairment of coordination, sight, hearing and speech; shaking, itching, burning, skin discoloration, edema, and desquamation. In cases where mercury blocks the degradation pathway of catecholamines (sympathomimetic fight-or-flight hormones released by the adrenal glands in response to stress), epinephrine excess can cause sweating, increased heart rate, hyper-salivation and high blood pressure. Long term or acute mercury poisoning can result in hypertension and cardiovascular disease and/or permanent damage to the nervous system, brain, kidney, and lungs. Fetal exposure to methyl mercury results in birth defects such as cleft, IQ deficit, and decreases in language skills, memory function and attention (Clifton and Jack 2007).

Potential cases of acute mercury poisoning were noted during the field survey. Both cases are suspected to have resulted from direct exposure to mercury fumes, as opposed to dietary sources. In one case, a 56 year old man who had been working as a miner in Puruk Cahu was forced to stop working and leave the mining area due to severe seizures. He had been working directly with large amounts of mercury and in close proximity to amalgam burning. His acquaintances did not understand the cause of his symptoms and he was seeking hospitalization. In a second case, a nine year old girl from a mining family in the town of Kuala Kurun had a debilitating case of the palette cleft. This deformative birth defect of the dental palette occurs during weeks 6 to 10 in utero. Though cleft was a common birth defect during and in the aftermath of the Minimata health crisis, the causal link between mercury poisoning is not well documented in the literature. No medical or diagnostic expertise was employed in either of these personal encounters.

#### **1.2.10 Research on ASGM and Mercury in the Tropics**

Several studies of small-scale gold mining and mercury have been done on mining areas in the tropics. These are often conducted through a lens of presumptive contamination, and studies rarely differentiate natural sediment associated mercury from mercury introduced by miners. This is often difficult to do because how the tailings were originally processed is often not known. In most ASGM contexts around the world, the majority of tailings have not been brought in direct contact with mercury, and therefore are not likely to differ significantly with respect to mercury content, when compared to proximal unprocessed sediments exposed to similar depositional conditions.

Mercury pollution typically occurs through two avenues when it is used for amalgamation: liquid elemental mercury or mercury droplets contaminate the area surrounding its' use, and mercury vapour is diffusely released when amalgam is roasted. As a consequence, deposition of atmospheric mercury has been shown to be elevated within about 5 km of mining sites when amalgam is roasted, but mercury concentration decreases with increasing distance (Lacerda, 1997).

The speciation work of Slowey and Rytuba (2005), based on column studies with placer tailings from mining areas in California, used sequential extraction to simulate (investigate) how natural processes might affect the mobility of sediment mercury present in tailings. The study found that readily soluble species including mercury oxides and chlorides comprised only 3-4% of total mercury; intermediately extractable phases including inorganic sorption complexes and amalgams comprised 75-87%; and highly insoluble mercury including cinnabar comprised 6-20%.

In numerous published ASGM studies, localized mining operations are explained and some attempt is made to quantify regional mercury contamination. Indonesian examples include Ayhuan, Atteng et al. (2003), and Whitehouse, Posey et al. (2006). In other studies mining practices are elaborated, and implementation of new technologies is introduced and tested in ASGM settings (Sousa and Veiga 2008).

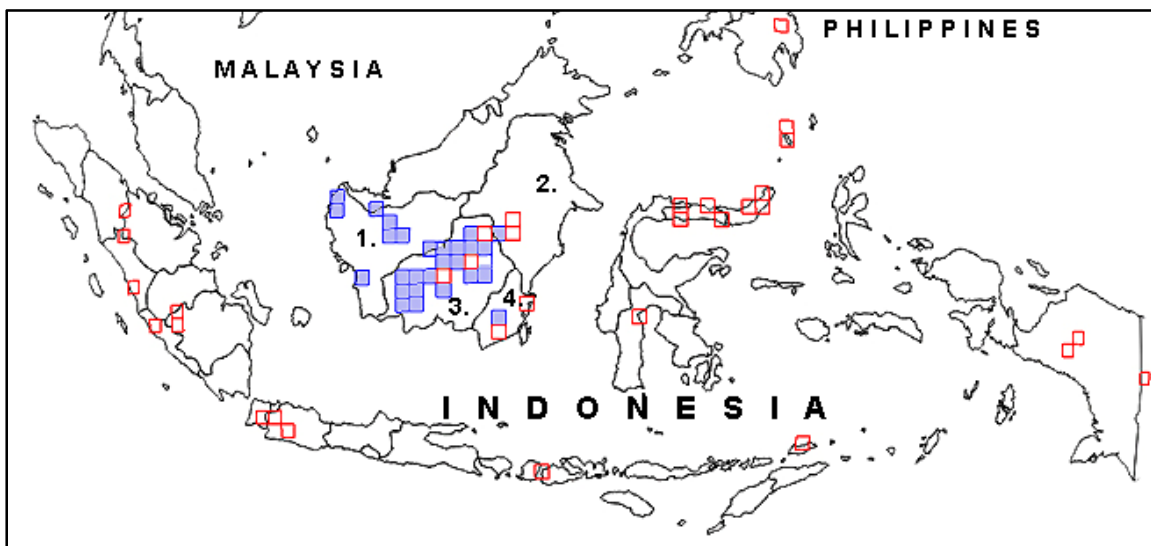
### **1.3 Study Area**

#### **1.3.1 Physical Geography of Central Kalimantan**

The province of Central Kalimantan is approximately 150,000km<sup>2</sup>, comprising nearly one quarter of Borneo. It is bordered by West Kalimantan, East Kalimantan and South Kalimantan, and the Sea of Java to the south – see figure 4. These Indonesian provinces share the island of Borneo with two Malaysian provinces and the independent Republic of Brunei, which dominate the northern part of the island. The province is covered by peat land, mangrove and swamp forests, dipterocarp forest, heath and montane forest, and shrublands. Expanses of peat-lands in low lying areas are among the fastest developing peatlands in the world. These areas are underlain by deep organic soils, producing tannin and DOM-rich (dissolved organic matter) river flows, with tea-coloured waters.

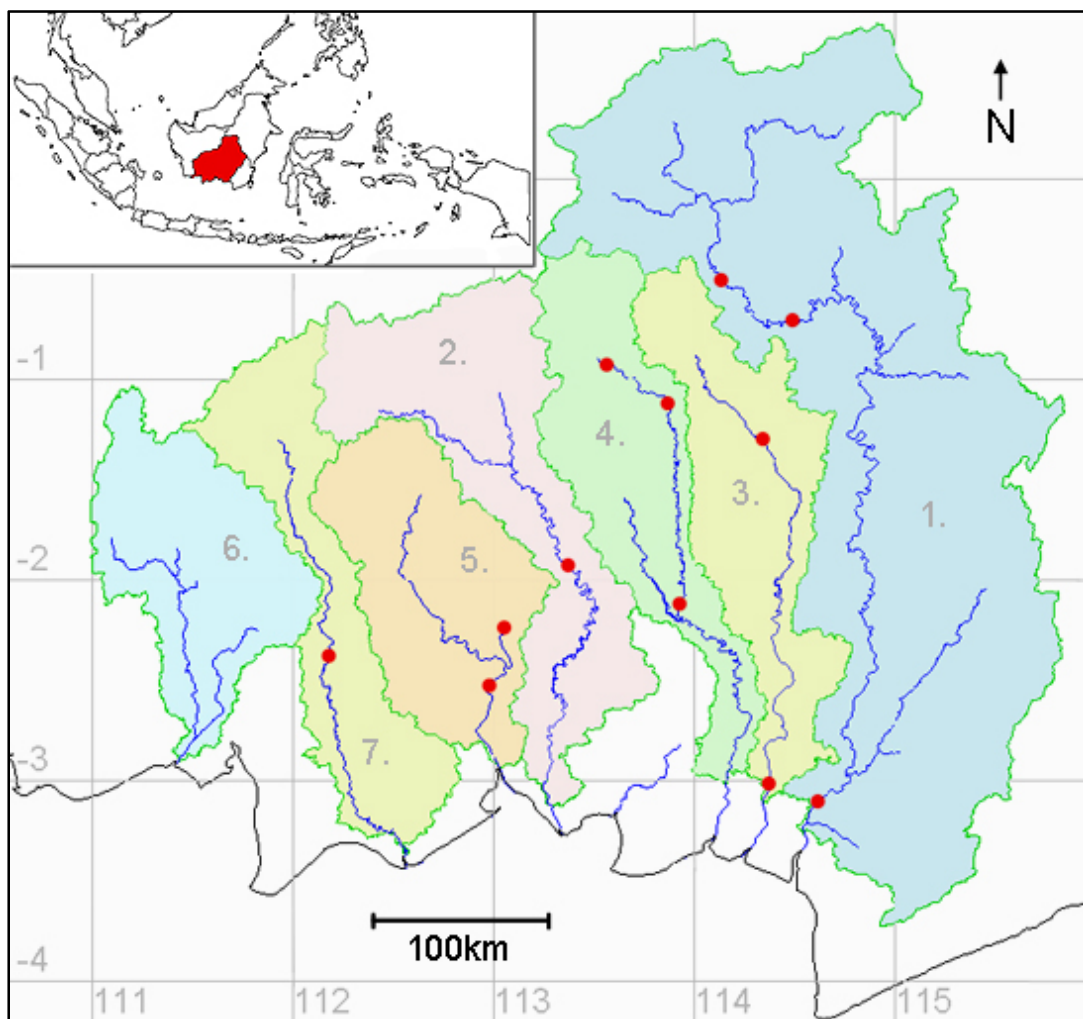
Gold mining is widespread across the Indonesian archipelago, including in Kalimantan, and exploration of many properties is ongoing. The World Lode Gold Database, created by Geological Survey of Canada (Gosselin 2005), identifies many of these gold deposits,

around which it can be assumed that ASGM is operating. The map of Indonesia depicted in Figure 4 is overlain by square polygons ( $1^\circ$  lat x  $1^\circ$  long) from the World Lode Gold Database in red, and square polygons in blue (shaded), appended based on the work of this thesis, including confirmation of ASGM activities through site visits and/or identification of ASGM in remotely sensed data (based on Telmer and Stapper, 2008).



**Figure 4. Map of Indonesia, with Borneo and Sulawesi in the center. Four provinces make up the Indonesian portion of Borneo. Provinces of West- (1), East- (2), Central- (3), and South- (4) Kalimantan.**

Central Kalimantan's seven largest river basins cover more than ninety percent of the province's area. All of these basins have their headwaters in hilly terrains of central Borneo and flow south to the Sea of Java. The river basin watershed boundaries form the basis of the provinces' administrative borders, and are shown in Figure 6. The Barito is the largest river basin in the province with an area of  $62,700\text{km}^2$  - roughly twice the area of Vancouver Island. The next six largest basins have areas between  $12,900$  and  $19,000\text{km}^2$  (see Figure 5). These basins, charged by intense heavy tropical rainfall, produce massive river channels with river mouths ranging in width from one to several kilometres across.



**Figure 5. Large river basins of Central Kalimantan, showing main channel sample locations. Numbered from largest to smallest, the basins are: 1 Barito (62,700km<sup>2</sup>); 2 Katingan (19,000km<sup>2</sup>); 3 Kapuas (15,800km<sup>2</sup>); 4 Kahayan (15,400km<sup>2</sup>); 5 Sampit (14,600km<sup>2</sup>); 6 Arut (13,500km<sup>2</sup>); 7 Seruyan (12,900km<sup>2</sup>).**

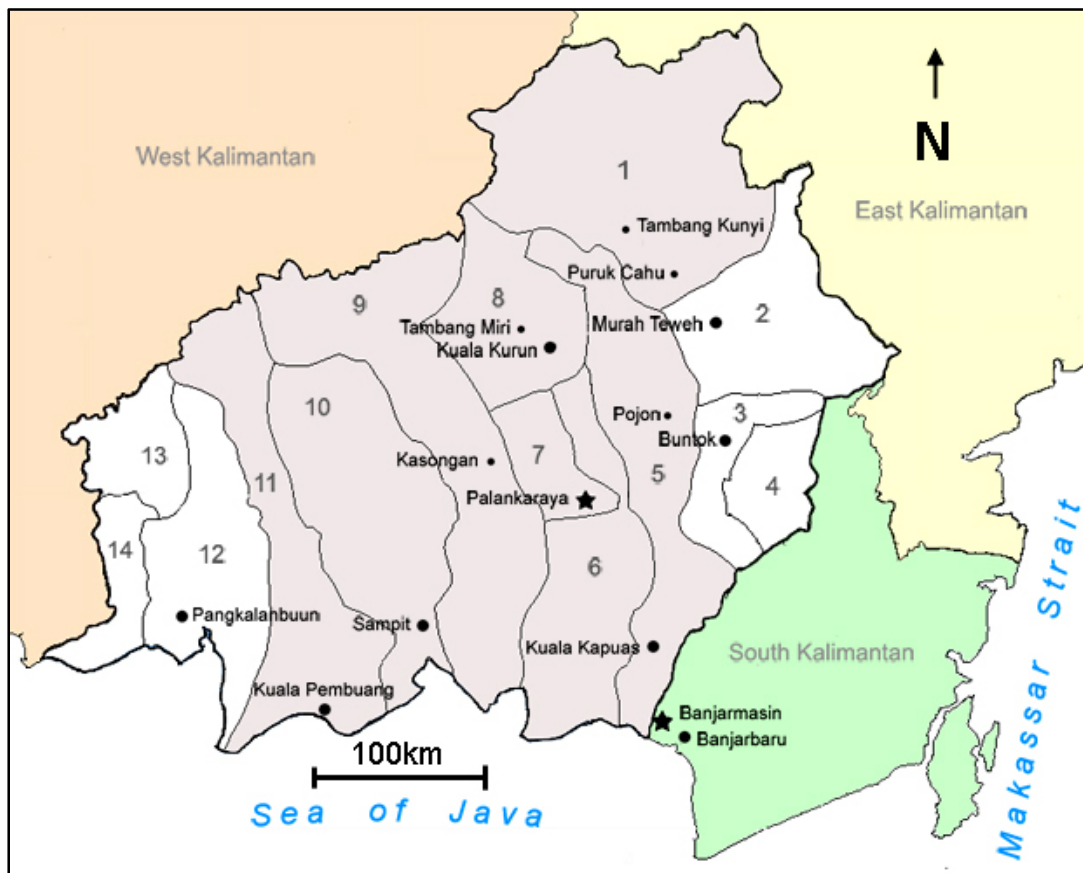
Climate in the region is determined primarily by east and west monsoons and by movements of the Inter-Tropical Convergence Zone. Mean temperature is 27 degrees and rainfall can be intense and sustained. Rain gauge data from two cities in the province agree well with remotely sensed precipitation measurements made by the Tropical Rainfall Measurement Mission (TRMM). These data suggest that coastal areas receive approximately 2500mm and inland areas up to 6000mm annual rainfall. Historically the months of June through September have been considered dry season but in recent years seasonal regularity has been less pronounced. Although mean

precipitation was lower during April through September of 2008 than during October through March, river levels were not low during field work, according to locals.

### **1.3.2 Administrative Setting**

Central Kalimantan is ethnically and linguistically diverse. Dayaks are considered the indigenous people of Kalimantan but this title refers to numerous distinct groups that have inhabited the coasts and forests of Borneo for centuries. The three largest Dayak tribes in Central Kalimantan are the Ngaju, Ot Danum and Dusun Ma'anyan Ot Siang. Chinese and Malayan people, as well as immigrants from other Indonesian islands make up a significant proportion of the population.

The province of Central Kalimantan is divided into 14 administrative districts also known as regencies. Law enforcement agencies and public service personnel operate mainly under regency jurisdiction although provincial and municipal level police also exist. Laws and permit processes which relate to mining activities therefore depend to a large degree on the head of the regency (Bupati), his staff and the policies they implement. Traditional leaders known as Demang also maintain a governing system of 67 areas known as Kademangan. This system recognizes and preserves the cultural customs and heritage of the indigenous Dayaks, to a limited degree, but is also used to claim land rights for mining.



**Figure 6. Map of Central Kalimantan's administrative regencies and significant cities, with visited regencies appearing shaded. Regency names (numbered) are 1 Murung Raya; 2 Barito Utara; 3 Barito Seletan; 4 Barito Timur; 5 Kapuas; 6 Pulang Pisau; 7 Palangkaraya; 8 Gunung Mas; 9 Katingan; 10 Kotawaringan Timur; 11 Seruyan; 12 Kotawaringan Barat; 13 Lamandau; 14 Sukamara.**

Much of the province is remote and not easily accessible. The quality of roads ranges from paved to impassable. Intense rainfall all year around makes road building difficult and crews are not well equipped. Boats are a critical mode of transit for goods and passengers along river channels, especially in areas roads do not reach, or are not maintained. As of February 2010 the provincial government is moving ahead with plans to develop a rail system which intends to bolster coal mining and palm plantation industries.

### **1.3.3 Land Use**

Vast areas of peat-land in Central Kalimantan have dried out in the past 15 years as a result of the Mega Rice Project, implemented between 1996 and 1998, in low lying areas within 150km of the coast. More than 4000km of canals were dug through peat-lands in the hopes of converting one million hectares of peat-land into productive agricultural land. The project was an unquestionable failure and has instead produced vast tracts of land prone to burning during dry months of the year.

Palm plantation is a rapidly emerging land-use in the province. Plantation land grew from less than 2000 hectares in 1991 to more than 450,000 hectares in 2007, according to Forest Watch Indonesia (Palmer and Engel 2007).

Peat fires associated with land clearing practices for land-use conversion often burn out of control in the province. These peat fires are very difficult to extinguish and are a huge problem in Central Kalimantan as they release vast quantities of smoke, CO<sub>2</sub>, and mercury from organic-rich peat soils, detritus and vegetation.

According to Regional Gross Domestic Profit (RGDP) figures for the province of Central Kalimantan for 2006, agriculture was the largest economic sector in that year, comprising 33% of the provinces RGDP. Hotels and restaurants comprised (18%), services (12%), transport and communication (10%), manufacturing (8%) and mining and quarrying (7%) (Brodjonegoro and Ford 2007).

Due to the informal status of ASGM, this sector is not accounted for in these provincial economic figures. The survey and assessment of the sector made in this thesis suggests that if ASGM were included, RGDP attributed to mining and quarrying would comprise around 15% of RGDP.

### **1.3.4 Geology of Borneo**

Borneo is at the centre of a South East Asian extension of Eurasia surrounded by long-lived Cenozoic subduction zones resulting from convergence of the Indian-Australian, Pacific and Philippine Sea tectonic plates. The island is the result of Mesozoic accretion

of ophiolitic, island crust and micro-continental fragments of south China and Gondwana origin, with their sedimentary cover onto the Palaeozoic continental core of the Schwaner Mountains in the southwest of the island (Hamilton 1979), (Metcalf 1996), (Hall and Nichols 2002).

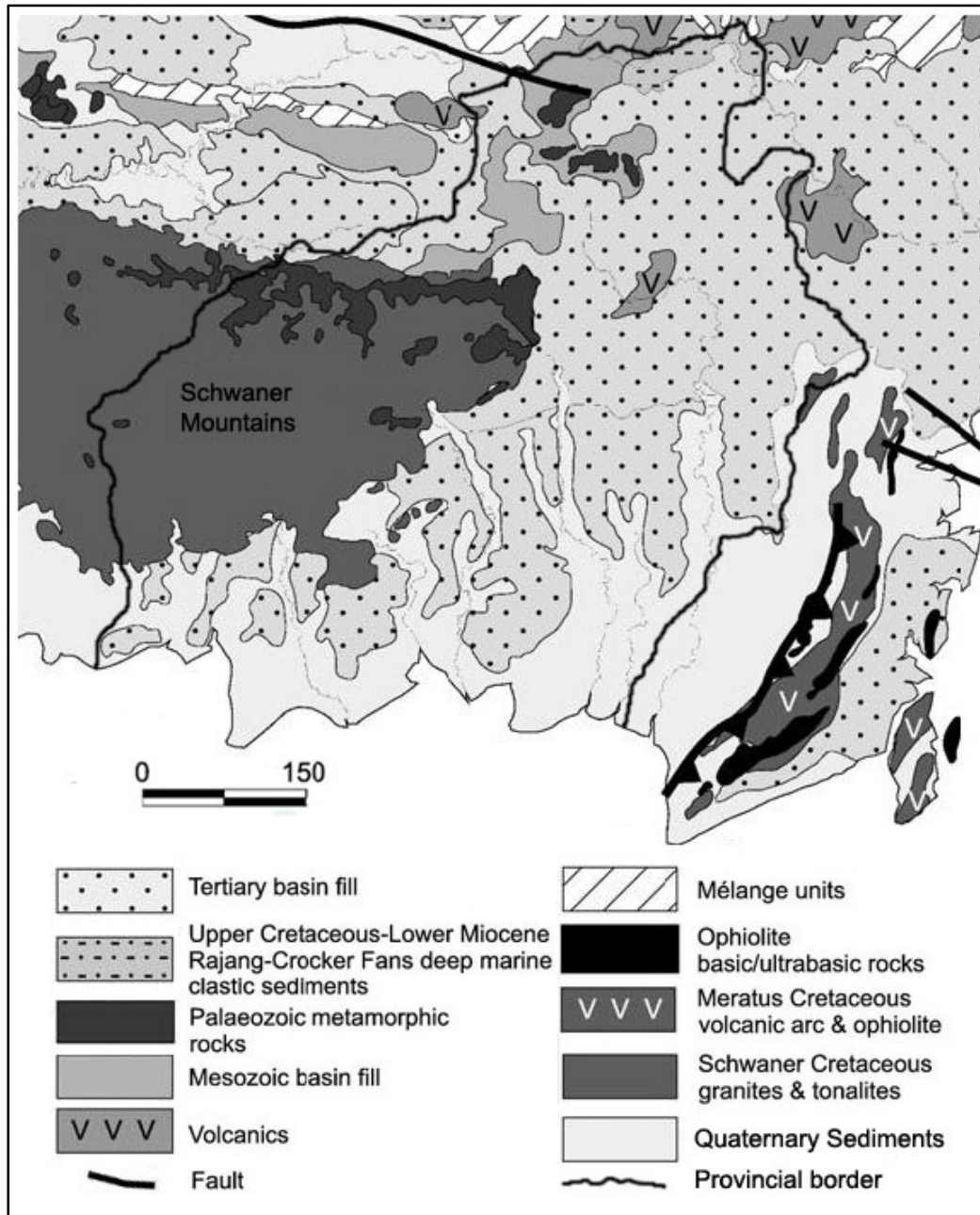


Figure 7. Simplified Map of Central Kalimantan's Geology, showing provincial border, altered from (Hall, van Hattum et al. 2008).

A thorough review of evidence by (Hall, van Hattum et al. 2008) concluded that sedimentary cover more than 5 kilometers thick covering several of Borneo's main river basins was derived dominantly from local sources – a previously debated hypothesis. According to widely held views, rapid mountain building caused by the southward subduction of the Miri-Luconia Block into the Sundaland Ophiolite occurred during the Oligocene and early Miocene (Carlile and Mitchell 1994). Subsequent erosion and deposition of clastic sediments into Borneo's basins increased Borneo's land-area as predominant sedimentation changed from extensive carbonate shelves to deltaic deposition and progradation (Moss and Wilson 1998), (Hall and Nichols 2002), (Hall, van Hattum et al. 2008).

### **1.3.5 Gold Deposits of Central Kalimantan**

Lode gold deposits discovered and exploited in Central Kalimantan are predominantly low-sulphidation epithermal vein deposits associated with Tertiary magmatic activity and subsequent alteration (Carlile and Mitchell 1994). The deposits exist within rocks of the Central Kalimantan magmatic arc. Their genesis stems from volcanism associated with the miri-luconia block subduction 25 to 10 million years ago (Carlile and Mitchell 1994). Successful large scale mining operations of these lode deposits include Masupa Ria (Thompson, Abidin et al. 1994), Mount Muro (Simmons and Browne 1990) and Kelian (Van Leeuwen, Leach et al. 1990).

Gold mineralization at Mount Muro is of particular relevance in this thesis because small-scale mining was surveyed there. Mount Muro is located in the upper Barito River Basin in the Regency of Murung Raya, ten kilometers west from the city of Puruk Cahu. Gold mineralization is concentrated in hydrothermal quartz vein systems hosted in andesites and volcanic breccias. The highest grade mineralization is associated with quartz and quartz-sulfides (Simmons and Browne 1990). A third generation contract of work agreement (COW) with the Indonesian Government covering 44,000 hectares remains in effect and is held (during the writing of this thesis) by Straits Resources of

Australia. During the field survey approximately 3000 artisanal miners were living and working within the COW, which encompasses several communities.

Placer gold deposits distributed widely throughout the province can be attributed to gold mobilized from hydrothermal lodes of the Central Kalimantan Arc. Most of Central Kalimantan is covered by low lying (<100m) and relatively flat Tertiary sandstones and mudstones. These sediments are bounded by Cretaceous granites of the Schwaner Mountains which trend SW-NE along the provinces northern border and Cretaceous rock assemblages of the Meratus Mountains to the East. Basinal rocks in the sedimentary strata belong to the Tertiary Warukin Formation, deposited from the earliest weathered materials of the Schwaner Mountains and the Central Kalimantan Range (Moss and Wilson 1998). Overlying these sediments are extensive fluvial and shallow marine sediments deposited on an emerging land surface since the early Miocene (Seeley and Senden 1994). These sediments are clays, sandy clays and lignites and comprise the Dahor Formation. Pleistocene to recent incision of the Upper Dahor Formation by Central Kalimantan's river systems has resulted in terraced deposits of quartz and zircon rich sands with intercalated clay horizons, quartz pebble conglomerates and sandy gravels. From the Holocene to the present, two major cycles of marine transgression and regression have affected the distribution of these sediments via coastal build-out and aggradation (Satyana, Nugroho et al. 1999). Many of the quartz pebble conglomerate reefs are gold bearing. Though much younger, the diagenetic mechanisms which formed these reefs appear to share developmental similarities to the Archean Witwatersrand conglomerate reefs of South Africa. On this basis, conjecture can be made regarding the evolution of Kalimantan's conglomerate reefs, as follows. Large basins of Borneo including the Barito River Basin received huge volumes of weathered material during Tertiary mountain building, especially from Central Kalimantan Arc terrains. Clastic sediments containing gold were eroded from the Schwaner and Muller Ranges and washed into sedimentary basins forming large alluvial fans. These fans extended from the hills over large distances until decreasing slope led

to braided channels and eventually to meandering rivers that fed into mangroves and swamps. This gravitational gradient would have provided a first concentration mechanism for gold. Chemical and physical weathering further reduced the mass of gangue minerals bearing gold. Further concentration occurred during periods of marine transgression and regression during which lighter less-resistant materials were winnowed away by currents and wave action, leaving behind minerals resistant to weathering, which also happen to be associated with gold. Due to its high specific gravity, gold particles remained in proximity with resistant reef sediments, sometimes cemented by secondary minerals or buried in fluvial clays during delta and river migration. As a result, vast areas of gold bearing reef sediments lie many kilometers from modern river channels in Central Kalimantan, and are covered by jungle or other wetland ecosystems.

Gravitational and mechanical processes are not the only mechanisms that control the distribution and extent of alluvial placer deposits (Boyle, 1979). Gold particles from both terrace and channel sediments in the Galangan region of Central Kalimantan were analyzed and studied by (Seeley and Senden 1994). The authors cite textural features of gold particle surfaces, the occurrence of spherical gold particles, and the high purity of gold particles as evidence for their postulation that chemical mechanisms are responsible for aggregation of gold colloids, explaining a significant portion (~15%) of fine gold in the terrace sediments analyzed. Acidic soils and humate-rich ground waters are suspected to enable dissolution and subsequent aggregation of gold colloids. Eh/pH boundary zones between acidic ground waters containing gold colloids and specific mineral assemblages with surface waters, are suspected to support coalescence and aggregation of the gold colloids (Seeley and Senden 1994).

## **1.4 Erosion and Sediment Transport in Borneo**

### **1.4.1 Sediment Removal**

Rivers are the principal conduits of landmass removal and nowhere do they accomplish this more effectively than on sloped landscapes of the humid tropics. Due to steep relief, relatively young and erodible rocks, and heavy rainfall – the rivers of the East Indies transport a disproportionately large amount of sediment to the ocean (Milliman and Meade 1983), (Milliman and Syvitski 1992). Despite draining less than 2% of the world's land area, (Milliman, Farnsworth et al. 1999) postulate that the East Indies (Sumatra, Java, Borneo, Sulawesi, Timor and New Guinea) may be responsible for the delivery of 20% of global sediment to the world's oceans. Considering this and the higher than global average mercury concentration of transported sediment from the region, it follows that sediment mercury from the East Indies might account for upwards of a quarter of global sediment-bound mercury delivered to the world's oceans. Though this dramatic claim is supported by sediment transport studies from Borneo, this hypothesis appears to be biased towards small river catchments in the Malaysian province of Sabah (Malmer 1990), (Douglas, Spencer et al. 1992), (Douglas, Bidin et al. 1999). Normalized sediment flux measurements made by these authors vary from 58 to 1600 t/km<sup>2</sup>/a. Extreme variability of these estimates is attributed to disturbances caused by forestry and plantation development, sedimentary lithologies susceptible to weathering, and intense rain storms. As an example, (Douglas, Bidin et al. 1999) present suspended sediment flux measurements from a 721km<sup>2</sup> Malaysian watershed suggesting a transport rate of 592 t/km<sup>2</sup>/a over an annual period which included a single 170mm rainstorm responsible for 40% of the annual flux. From the perspective of landscape evolution, incorporating rare catastrophic events, Hall and Nichols (2002) estimate the modern sediment removal rate from Borneo to average 850 t/km<sup>2</sup>/a.

### **1.4.2 Measurement of Sediment Transport**

Most sediment transport studies distinguish only two components of sediment transport: suspended sediments and bed load sediments. This is because proportions of

suspended bed-material and wash load (suspended sediments) vary with stream energy and thus change along river reach and with flow stage. In lowland reaches of the Mississippi River long term studies have shown that bedload transport accounts for only 5-15% of total sediment flux (Mossa 1996). Likewise in large rivers of the German lowlands suspended sediments make up more than 85% of the total sediment loads (Marxsen, Schmidt et al. 1997) (Asselman 1999).

River sediment studies commonly focus on suspended sediments because this fraction is most accessible from a sampling perspective and because it dominates the transport of pollutants. Samples are collected by filtering a known volume of water through a pre-weighed filter membrane to collect the suspended particulates which can then be analyzed. Alternatively, automated samplers which use photometric methods to estimate total suspended sediment (TSS) on the basis of light attenuation as a proxy for turbidity are becoming increasingly popular, as are doppler methods that estimate particle density and velocity.

Bedload refers to larger particles confined to the river bed and transported dominantly by saltation. The most accessible method of sampling this material is by collecting grab samples. After size-fraction analysis, the bed-sediment size fraction data can be used to inform sediment transport models and formulae. These models and formulae incorporate hydraulic parameters of river reaches being studied, along with representations of the size distribution to predict or estimate sediment transport. The hydraulic channel parameters used typically include aspects of channel geometry such as slope, width and depth, and flow properties such as discharge and mean velocity. The application of transport formulae must consider the river type and sediment size ranges. Irrespective of which sediment component is studied, measurement interval is a critical consideration when making transport or flux measurements. Measurement campaigns which utilize hydrologically based as opposed to calendar based sampling, are preferred, especially in the case of short-term or infrequent sampling campaigns (Horowitz 2003). If sediment transport data is collected from a range of flow conditions the relationship

between water discharge and sediment flux can be plotted as a sediment rating curve. These curves can be used to predict sediment flux for a given time interval using measured or estimated river discharge hydrographs.

## **1.5 Mercury fluxes in Central Kalimantan**

In order to avoid presumptive treatment of ASGM mercury as a source of environmental contamination, it is useful to investigate and quantify natural mercury cycling processes occurring in the study area. To do this, mercury processes are discussed in the context of Central Kalimantan using references to peer reviewed literature. Understanding these processes and the quantities of mercury involved is helpful when interpreting mercury use and emission from small-scale gold mining, and mercury transport associated with river sediments.

### **1.5.1 Deposition, Sequestration and Volatilization**

Primary factors controlling volatilization, speciation and adsorption state are soil permeability, temperature and microbial activity (Grigal 2002). If oxidized mercury is reduced to Hg(0) high vapor pressure subsequently leads to volatilization. Reduction of oxidized mercury can be induced by biotic and abiotic agents including microbes, sunlight, and dissolved organic matter.

Most of the atmospheric mercury and mercury deposition research done in the tropics has been conducted in the Amazonian region. Many parts of the Amazon have been subjected to mercury emissions from gold mining for many decades. Demonstrating this point, mercury sampling and speciation analysis on eight airplane flights over the Amazon in 1995 suggested 63% of total atmospheric mercury originated from gold mining (Artaxo, Calixto de Campos et al. 2000). This may be a reason that assessments of mercury deposition rates in the Amazon vary widely from around  $10\mu\text{g}/\text{m}^2/\text{a}$  (Lacerda, Ribeiro Jr et al. 1999) up to  $151\mu\text{g}/\text{m}^2/\text{a}$  (von Tumpling, Wilken et al. 1996). By analyzing mercury in rain water, Nakazono, Fosberg et al. (1999) estimated annual

deposition in the Negro River basin, a region without mining influence, to be  $14.7\mu\text{g}/\text{m}^2/\text{a}$ .

Concentrations of mercury in precipitation vary widely from around 1 to more than 1000ppt, but are more typically between 5 and 15ppt (Downs, Macleod et al. 1998). High mercury values in rain detected in their study were measured close to mercury sources, where oxidized mercury was being rained out of the lower atmosphere.

Due to the large number and area of receptor surfaces dry deposition is of greater consequence than wet deposition in forested areas. Based on review of numerous studies, total atmospheric mercury deposition to soils of forested areas is roughly four times the that of deposition in open areas, due to wash-off of dry deposition and litter-fall (Grigal 2002). A significant portion of mercury deposited by wet and dry deposition moves towards and is sequestered by soils. The mobilization of adsorbed mercury in tropical soils is dominantly controlled by erosion of mercury-bearing mineral phases which depend to a large degree on soil penetration during and after rain events (Guedron, Grimaldi et al. 2006).

Study of soils in East Kalimantan have shown dissolved organic carbon leached from the organic soil horizon, by high precipitation rates, carbon inputs and rapid decomposition (Fujii, Uemura et al. 2009). It was also determined that dissolved organic carbon (DOC) transport was responsible for the translocation of Al and Fe in the soils studied. Mercury may also be translocated through and from soils by this mechanism. This is supported by studies including Yongkui and Dingyong (2008), and Gu et al., (2010).

Biomass burning (BMB) of peat fires causes one of the largest regional fluxes of mercury (volatilization and deposition) in Central Kalimantan. In the recent decade (2000-2010), drought and land-use changes including the use of fire for land-clearing, have caused extensive and persistent peat fires. Using data from recent fire seasons, the potential for soil mercury volatilization is estimated here.

By combining data from the Global Fire Emissions Database (GFED) with mercury emission factors on sub-continental scale, (Friedli, Arellano et al. 2009) estimated that biomass burning has been responsible for global emissions of  $675 \pm 240$  tons of mercury between 1997 and 2006, with a disproportionate contribution from South-East Asia. Their global BMB model allocates a mercury emission factor of  $315 \mu\text{g Hg}$  per kilogram of burned fuel for the South-East Asian region (EQAS). This is the highest regional value in the global model. Based on fire data spanning 1997 -2006, this model estimates mean annual Hg emissions from BMB in EQAS to be  $192 \pm 216$  tons per year. This is 28% of modeled global BMB emissions, despite the EQAS fires representing only 11% of total burned carbon and only 1.2% of burned area. Massive peat fires in the province of Central Kalimantan in 1997, 2002 and 2006 are a primary contributor to these results. Mercury emissions from Central Kalimantan's peat fires are estimated here by multiplying carbon emission estimates of the South Kalimantan sub-regional area delineated by Field and Shen (2008) by a mercury emission factor of  $315 \mu\text{g Hg}$  per kilogram of burned fuel, a value derived by Friedli, Arellano et al. (2009).

Fire Season	Carbon Burned (Tg)	Hg Emission Factor $\mu\text{g Hg/Kg fuel}$	Total Hg (tonnes/season)
June-November 1997	480	315	151.2
June-September, 2001	35	315	11.0
February-March, 2002	153	315	48.2
June-September, 2003	32	315	10.1
August-November, 2004	62	315	19.5
August-November, 2006	274	315	86.3

**Table 1. Estimates of mercury evasion from soil and vegetation during recent extreme fire seasons in the South Kalimantan sub-regional area from Field and Shen, (2008). Central Kalimantan makes up more than 75% of their sub-regional area.**

Mercury release from biomass burning is a spatially discrete phenomena, with regional meteorology playing an important role determining the duration and distance of transport and mechanisms of deposition (wet verses dry). The total amount of mercury volatilized, and the proportion that experiences short vs. long range atmospheric transport, are highly variable and not well known.

### **1.5.2 Weathering of rocks**

Rates of chemical and physical weathering (denudation) in Central Kalimantan result from high temperature, intense rainfall, rapid rates of uplift, particular lithologies, and relatively acidic waters. If a combined chemical and mechanical denudation rate of 326 meters per million years - made for Borneo by (Hall and Nichols 2002), and an average rock Hg concentration of 50ppb (based on (Smith, Kesler et al. 2008), then 4.4 tonnes of mercury is mobilized each year resulting from the denudation of  $8.8 \times 10^7$  tonnes of rock covering the area of Central Kalimantan.

### **1.5.3 Sources of streamflow mercury**

Stream-flow mercury is total mercury flux transiting rivers, including dissolved and particulate phases. The source components of river discharge are base flow, interflow, and overland flow. Baseflow is principally sourced from ground water and is generally low in mercury. Interflow has travelled through soil at shallow depths relative to base flow and has intermediate mercury concentrations. Overland flow is sourced principally from run-off, and provides the majority of mercury to stream and river systems, dominantly associated with particulates in suspension (Grigal 2002).

### **1.5.4 Dissolved phase Hg stream flow**

The concentration of dissolved mercury species in stream and river waters depends on the amount and species of mercury present, on other ions and molecules present (alkalinity), and pH. Mercury species tend to be insoluble in water, although humic acids have been shown to enhance their solubility (Melamed, Villas Bôas et al. 1997). The role played by dissolved organic matter (DOM) for binding and transporting available mercury has been demonstrated in several studies (You, Yin et al. 1999), (Ravichandran 2004). Strong adsorption affinity of both DOM and DOC for mercury is the result of electrostatic attraction and ligand exchange between carboxyl and hydroxyl groups and mercury phases (Kaiser and Zech 1998). DOC adsorbed mercury tends to be less reactive with sediment mineral surfaces and this lowered affinity for interaction with sediments

is a mechanism by which mercury can be mobilized further through aquatic environments (Melamed, Villas Bôas et al. 1997).

Collection of water samples for dissolved mercury analysis is difficult and complicated due to the risk of sample contamination and typically represents only a small fraction of streamflow mercury. Field and logistical conditions in this sampling campaign did not allow for water samples to be analyzed for dissolved mercury.

If dissolved concentrations of 5ppt are assumed, based on literature review, then roughly 1 tonne of dissolved mercury is transported to the Sea of Java from Central Kalimantan's major rivers each year.

#### **1.5.5 Particulate phase Hg stream flow**

The transport of eroded rock, sediments, topsoil, and organic material in the regions' rivers represents a major mercury flux in the study area. Numerous studies from tropical watersheds have shown that particulate mercury is dominantly transported adsorbed to clay minerals or associated with particulate organic matter (POM). In mercury contaminated region around primary mercury mines in China, mercury associated with particulate material was found to be an important vector for mercury migration from the abandoned Hg mine sites (Feng and Qiu, 2008). In Chapter 3 of this thesis, analysis of sediment samples and hydrologic modelling are used to estimate sediment and mercury flux in the regions large rivers.

#### **1.5.6 Dissolved Organic Matter**

The strong binding of mercury to organic matter, and dissolved organic matter (DOM) in particular is critically important to its behavior in the terrestrial environment (Meili 1991). Dissolved organic matter (DOM) plays a strong role in adsorption and desorption of mercury from tropical soils, which has ramifications for mercury flux. In the work of Gu et al. (2010), waters with high DOM concentrations reduced the adsorption capacity of soils by as much as 40% in podzolic soils and slightly less in ferralitic soils. Further, the presence of DOM in fact promoted mercury desorption from the soils (Gu et al., 2010).

The binding of Hg to organic matter is associated with reduced sulphur groups that bind Hg(2+) (Skylberg et al. 2000). Many streams and rivers in Central Kalimantan have very high levels of DOM and tannins, evidenced by their tea color. The expected effect of this is an increase in mercury flux from soils and landmass.

## **Chapter 2. Artisanal and Small-scale Gold Mining in Central Kalimantan, Indonesia**

### **2.1 Introduction**

#### **2.1.1 Chapter preface**

An effective approach to developing pragmatic knowledge of ASGM in a region is to spend time with miners, processors and gold shop operators in the places they work and live. After observing and communicating with miners at their work sites, it becomes possible to make credible assessments of their approach, efficacy and impacts.

Information presented in this chapter was collected by visiting, observing and engaging with small-scale miners in the province of Central Kalimantan in June, July and August of 2008. In order to provide context, a brief history of ASGM in Indonesia is first presented. In the body of the chapter, detailed information from the surveyed mining operations is presented and explained. The geology of gold deposits dictates how miners exploit the ore deposit and process the gold bearing ore. For this reason ASGM operation descriptions are categorized based on three generalized ore types. After representative operations of each type are presented and discussed, survey information is used to estimate the amount of gold produced and the amount of mercury used by ASGM in the province in 2008.

#### **2.1.2 History of ASGM in Indonesia**

Alluvial gold deposits have been mined in Kalimantan for centuries. Prior to arrival of the Dutch in the early 17th century, immigrants of Chinese heritage mined alluvial gold in several districts of West Kalimantan (Van Leeuwen 1994). During the 1980's discoveries of epithermal gold and a shift in government policies relating to mineral contracts brought a gold rush to Indonesia. Between 1984 and 1987 more than one hundred Contract of Work agreements (COWs), covering 36 million hectares were signed by the Indonesian Government (Manaf 1999). In addition to these, numerous

small-scale mining permits were awarded to Indonesian individuals and companies. These permit holders hired local and immigrant workers, which were plentiful due to transmigration programs. It soon became clear that activities carried out by permit holders impinged on the rights of COW holders, and so the government introduced a process called Koperasi Unit Desa (KUDs), in 1989. This attempt to organize small-scale miners by legislating a co-operative model was not successful, and most miners chose instead to operate without permits, and/or rely on arrangements with local authorities (Manaf 1999).

On October 19, 1987 global markets suffered their largest one-day percent decline in stock market history. Although the gold price remained high relative to most commodities, many mining companies reduced their activities in Indonesia in the years that followed. At the time, due to their lower capital needs, small-scale miners moved into and began mining areas previously occupied by mining concessions (Manaf 1999).

Small-scale miners continue to operate in close proximity with large-scale mines in many locations in Indonesia, including Kalimantan. Direct overlap and in some cases conflict with large scale mining companies and their security forces, and police and military, have and continue to occur (examples include Kelian, Indo Muro, Grasberg).

### **2.1.3 Legal status of ASGM in Central Kalimantan**

The Indonesian political and regulatory landscape has undergone major changes since the transformation from Suharto's authoritarian rule to the current system of democracy in 1998-1999. Powers of the central government have been increasingly decentralized. In January 2009 after four years of parliamentary debate Law 4/2009 on mineral and coal mining came into effect, replacing its 1967 predecessor. There are seven articles in the law which relate specifically to ASGM. The articles can be summarized as follows: (i) areas up to 25 hectares can be designated for small-scale mining use; (ii) these must be approved by the Bupati's office (head of local regency) after a period of consultation; (iii) all laws, regulations, and permit granting procedures are governed by regency level authority.

At present the responsibility to develop and enforce ASGM policies and legislation falls on Central Kalimantan's fourteen regency level governing bodies. Decisions made by regency politicians are currently shaping development of the sector. During the 2008 survey (this thesis) Law 4/2009 was not yet in effect, and regional authorities were not formally mandated to develop or legislate regionally tailored ASGM policies. However, the impact of this change appears to have been minimal, based on correspondence with colleagues working in Central Kalimantan.

## **2.2 Survey Methods**

### **2.2.1 Language and institutional support**

Two weeks of Indonesian language tutorship were undertaken in Jakarta in advance of traveling to Kalimantan. Yayasan Tsimbuka Sinta (YTS) is an independent community development subsidiary of the Kalimantan Gold Exploration Company based in Palangkaraya, the capital of Central Kalimantan. YTS provided support for acquiring visa and travel permits. They also provided initial logistical support in Palangkaraya.

### **2.2.2 Satellite imagery**

Prior to the survey campaign, more than fifty ASGM regions in the province were identified using satellite imagery. This work was part of a project which combined field work and remote sensing to make ASGM assessments for Brazil and Indonesia (Telmer and Stapper, 2007). Additionally, GIS tools were used with digital elevation data to delineate and map watershed boundaries, and channel networks. Maps were assembled and printed, and brought to the field to support exploration into remote ASGM areas.

### **2.2.3 Travel and engagement with gold mining communities**

Mining operations were visited in the regencies of Kotawaringin Timur, Katingan, Gunung Mas, Kapuas and Murung Raya. Modes of transport used to travel into and around these rural mining areas included informal taxi vehicles (*taxi hitam*), diesel powered river boats (*krotok*), motocross bikes and mopeds (*sepetak motor*), and floatplane (*pesawat*). In each regency, check-in with district police was expected and

permission was granted to investigate mining operations. Men familiar with local mining were employed as guides to mining areas. Gold trading shops and mining equipment retailers were consulted about regional mining activities and the local gold economy.

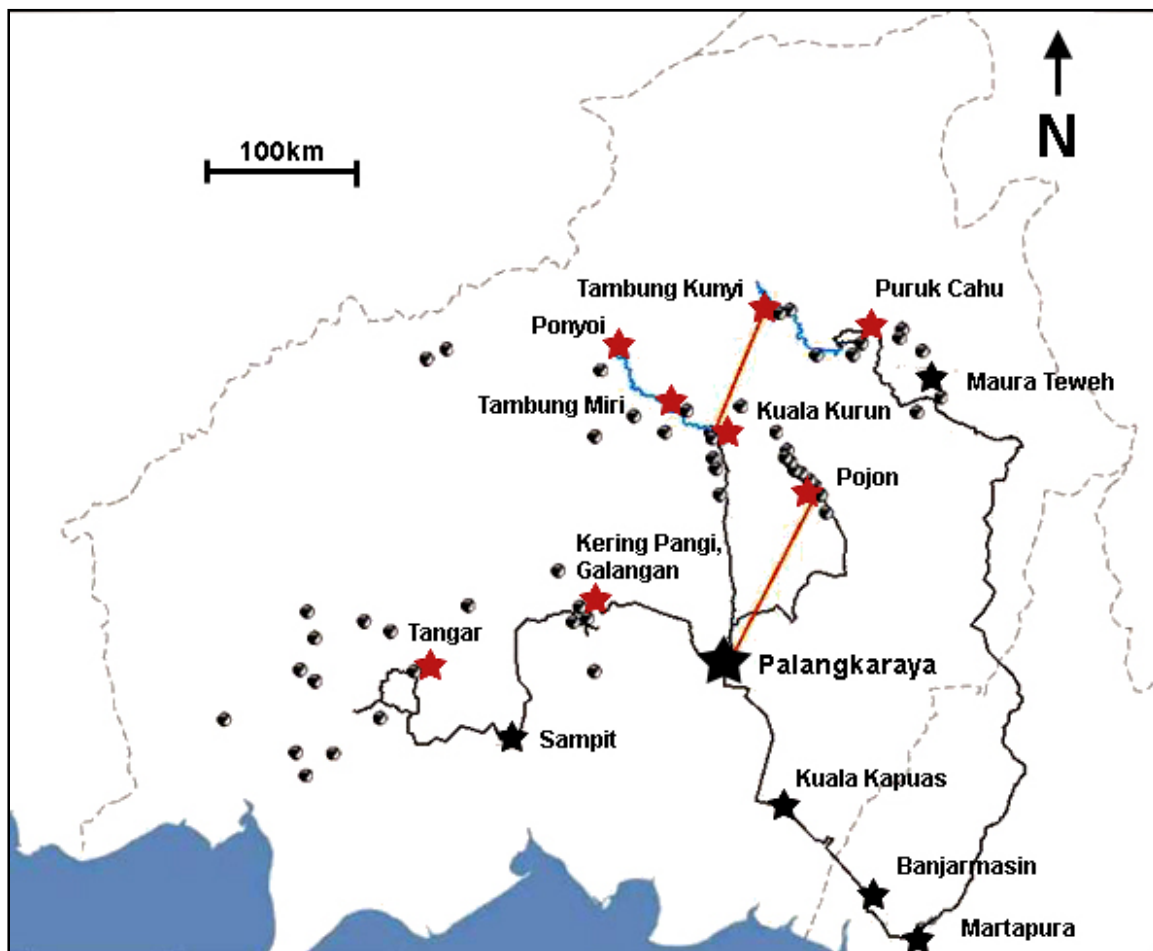


Figure 8. Map of Survey Route collected using GPS. Grey lines represent travel by road, blue- travel by river boat, and red- travel by small airplane; grey circles represent ASGM areas detected using satellite imagery; stars represent cities; red stars represent cities or towns which are key support centers for ASGM activities.

## 2.3 Results of Survey

### 2.3.1 ASGM labor force

Based on survey observations, at least 75% of the miner workforce in Central Kalimantan were young men aged 18-35. In most areas a similar proportion (around

75%) of the miners came from outside the mining area from large population centers such as Banjarmasin (Capital of South Kalimantan near the mouth of the Barito River), and the islands of Java and Sumatra. These young men left their homes and families where employment opportunities were sparse, in attempts to earn money to return home with. Women and children were not observed working as miners in ASGM camps, although it is common for women to provide food services, and families commonly live in camps which are essentially processing areas.

Investment in operation equipment is usually made by an individual who hires a team of miners and acts as site boss. Payment schemes and wages vary but are based on commissions and/or the daily recovery of gold. Most miners were earning between five and ten dollars per day, while bosses were earning many times this amount. Most operation schemes pay operation expenses, and then divide remaining profit between owner, boss (team boss is not usually owner of equipment), and miner group.

### **2.3.2 Classification of ASGM operations**

The mine operation survey is classified based on the three principal ore types being exploited in the province. This scheme is used because each ore type is mined using a distinctive approach. The ore types are:

**(1) Buried placer gold (paleo-placers).** Gold is hosted in sand and quartz pebble materials of paleo river beds and terraces, or marine beaches – mostly at depths between 1 and 10m. Miners dig pits to access layers of mineralization below the soil profile using hydraulic water jets. Sediments are subsequently pumped over large sluice boxes to produce a heavy mineral concentrate containing gold.

**(2) Alluvial gold in river banks and channels.** Gold particles in modern alluvium are accessed primarily using floating rafts called dredges. These are equipped with diesel motors used to suck and pump channel sediment up to the dredge where the slurry is passed over large sluice boxes.

**(3) Lode gold vein deposits hosted in hard rock deposits** (primary gold deposits). These rocks are gold is most typically of hydrothermal origin. Vein and parent rocks are extracted by chisel and hammer, then bagged and transported to processing centers for milling and amalgamation.

The three following sections are used to describe representative mining operations visited across the Barito, Kapuas, Kahayan, Katingan and Sampit river basins. To avoid repetition, not all of the mining operations visited are described.

### **2.3.3 Buried placers**

Buried placer deposits are paleo-placers which have been overlain by pedological (soil forming) processes. Although many of these deposits surround and intersect with modern stream and river channels, while many others are not presently located near active channels. Therefore the distinction between buried placers and alluvial placers made here is admittedly subjective, in areas along channels. The distinction made here, and used to classify operations described in this chapter is based on the dominant methods used to exploit the deposits: pits are dug to exploit buried alluvials, and floating dredges are used to exploit alluvial placers.

Buried alluvials in the sedimentary strata are widespread in Central Kalimantan and are the most widely exploited source of ASGM gold in the province. Pit operations were visited in six regencies of the province: Murung Raya, Kapuas, Gunung Mas, Katingan, Kotawaringan Timur, and Seruyan. Four of these areas are representative of buried alluvial placer mining across the province and are described below.

#### **Galangan-Hampilat mining area (Katingan River basin), Katingan Regency**

The Hampilat - Galangan mining area is the largest and most historically significant ASGM location in Central Kalimantan. For this reason it is described first, and its description is accompanied by subsections which explain aspects of the region in detail.

The Hampilat - Galangan mining fields are located one hundred kilometres west of Palangkaraya, the province's capital city. As of 2007 the mine fields covered approximately 200km<sup>2</sup> (Telmer and Stapper 2007). It is possible to measure the mine

field's area using satellite imagery because reflective white sands have been left exposed without topsoil, resulting in abrupt contrast with the surrounding tropical heath forest. On the north-eastern border of the mining area, the village of Kereng Pangi acts as an important hub for miners. In 2008 the town had a resident population of approximately 5000 people.

Small-scale miners began working the banks of the Hampilat River in the mid 1980s. Shortly thereafter a joint venture company defined an alluvial gold resource along the river of 18.4 million cubic meters grading  $0.242\text{g/m}^3$  Au - an estimated resource of 4.5 million troy ounces (Seeley and Senden 1994). Large scale dredging operations commenced in 1988 but mine production lasted less than two years due to resource overvaluation, difficult ground conditions, and the Asian financial crisis. After the company left, local and immigrant miners flooded into the area. Soon, profitable ores were discovered in buried terrace sediments several kilometers from modern river channels. This led to rapid clearing of forest so that these sediments could be reached. The mine fields expanded quickly, hosting up to 10 thousand miners between 1997 and 2002.



**Photo Panel 1. Aerial views of the Galangan mine fields. (top) Oblique photograph of the Galangan mine fields taken from low flying helicopter by Telmer in 2006; (below) Landsat imagery used to reconstruct mining history of the area: from 1989 and 1999 (NASA).**

During the field survey 33 buried alluvial operations were visited in the Galangan mine fields. Mining pits were most active along the south and eastern perimeters, where forest was being cut and burned to dig and expand new pit areas.

Pit operations in Galangan excavate sediments using high pressure water hoses powered by diesel motors. The high pressure water jets are used to dig by breaking apart soil and sedimentary horizons. The resulting slurry of water and sediments is

pumped from the pit up to ground level where it pours over sluice boxes. The use of sluice boxes for primary concentration is ubiquitous in alluvial small-scale mining operations throughout Central Kalimantan. Wooden sluice boxes are covered by several pieces of carpet, which are often door mats or towels. Due to mass and geometry, heavy minerals including gold is trapped on the carpets while most of the sediment flows off the sluice box as tailings. The sluices used in Galangan are approximately one meter wide and 8 to 12 meters long. Tailings form large domes which fan out from the base of the sluice boxes, while silt and clays remain suspended in slurry water which flows into nearby creeks or settles in adjacent mine pits.

In most of the operations around Galangan financiers and team bosses do not have ownership of the land being exploited. A common arrangement is profit-share between land-owner and the mine financier or operator. Financiers and operators may have several active operations or only one, but employ teams of workers. Miners generally work in teams of three to seven. Younger workers often dig and break apart sediments with hoes and shovels while the more experienced workers operate water pumps and ensures that the sluices are operating well. After a day's work, sluice carpets are carefully washed to capture the gravity concentrate. This is done in lined pools to capture the heavy minerals, which can be reprocessed for additional gold and for zircon. Zircon is the locally used name which refers to several heavy minerals which are valued, sold, and exported for use in ceramics, abrasives, and other industries – principally in China.



**Photo Panel 2. Large sluice boxes are used to concentrate pit sediments. (left) Typically sluices are setup outside the rim of the pit. (right) In cases where pit management is used along with sediment barriers, sluices are setup inside the pit, so that the tailings do not restrict further pit development.**



**Photo Panel 3. Miners work in the pits to liberate sediments using water jets. Notice differences in stratigraphy between Galangan pits, separated by two kilometres. This variation can be primary but is also secondarily caused by ground water flows and bitumen development. Lignite coals can be found in pit bottoms.**

### **Generalized stratigraphy (Galangan)**

Soil horizons around Galangan can be generalized as Acrisols, defined by the presence of a subsurface layer of accumulated kaolinitic clays where less than half of the ions available to plants are calcium, magnesium, sodium, or potassium.

Soil and sedimentary stratigraphy are clearly evident in cross sections of the mine pits (see Photo panels 2 and 3). Regional stratigraphy can be generalized as follows: a dark organic rich soil with hummus with overlying duff layer represents the uppermost soil layer, and is 10-20cm thick. Below this is a second dark coloured soil layer with less organic matter (B horizon), and a light coloured eluviated horizon rich in quartz and chlorite (C horizon).

Beneath the thin and heavily weathered soil profiles, subsoil strata are variable but usually begin with a cemented sandstone layer, dark in color due to organic leachates. The thickness and hardness of this layer is highly variable and miners avoid processing it. The sandstone grades into a less consolidated sandy horizon, sometimes interspersed with clay lenses. These sands grade into mineralized zones of with smoothed quartz pebbles, cemented to varying degrees with clays. Below the mineralized strata hard clays and mudstone typically represents the basement rock unit in the area. In some pits, lignite coals are present in the sandstone and sandy quartz pebble layers. While similar coals are mined extensively by small-scale miners in East Kalimantan, there was no evidence that the coal was being collected or used as fuel in Galangan.

#### **Ore grade and gold recovery (Galangan)**

Among gold miners it is widely known that low grade placers possess a nugget effect resulting from variability of gold distribution. In Galangan, sluice box measurements were made at multiple operations to determine the amount of sediment processed, and therefore the recovered gold grade during a day of sluicing. On 1 meter wide sluice boxes, mean slurry flow depth was 2cm and mean velocity 1.3m/s. From these measurements the determined volume flow rate is  $26,000\text{cm}^3/\text{s}$ . Slurry solid content was approximately 5% by volume, and therefore dry solid flow rate was  $1,300\text{cm}^3/\text{s}$ . Based on sediment specific gravity of 2.7, it follows that the feed rate was 3.5kg/second, or 12.5 tonnes per hour. These measurements show that the large sluices in Galangan (operating with 25 horsepower pumps) are capable of processing up to 100 tonnes of sediment in an eight hour working day.

On this basis, an operation which recovers 10 grams of gold in a day achieves a recovered gold grade of 0.1 grams per tonne. This represents a profitable day. However, over two days of new pit development (as seen in Photo panel 4), total gold recovery was only two grams of gold (carpets only cleaned after day 2). Under the same assumption that 100 tons was processed per day, recovered gold grade was then only 0.01 grams per tonne. On days such as this the gold value is spent entirely on operation costs, and miners make little-to-no money. Alluvial pit operations in Galangan and elsewhere in the province typically operate between these limits. In rare occasions rich zones are encountered and a single sluice can capture upwards of one ounce (31 grams).



**Photo Panel 4. Miners beginning new pits in Galangan.**

In an effort to cross-check this statistic, several compound 500 gram ore samples were collected from ore layers (as pointed out by miners) in Galangan and two additional regions. These samples were digested to assay for gold by ICP-ES. Assay results yielded 0.079, 0.016, and <0.010ppm (grams/tonne), demonstrating the nugget effect, but falling into the expected range.

#### **Efficiency of pit operations (Galangan)**

Overlying soils and lack of effective pit management compromise efficiency of the open pit approach used for accessing buried alluvial ores. This is because processing

overburden sediments drastically reduces the effective ore grade, because low grade material must be processed (moved) in order to access high grade material. As miners dig towards the targeted ore layer, pits deepen and increase in diameter, causing pit walls to slump and collapse. All of this material must be pumped from the pit over the sluice box, resulting in lower ore grades than if the targeted ore layer could be processed independent of overburden sediments. The following example is based on a pit visit in Galangan, and illustrates this problem.

A large 1 hectare pit (see Photo panel 5) with a targeted ore layer of quartz pebble conglomerate averaging one meter thick contains 0.25 grams recoverable Au/ton. This layer is buried underneath several meters of overburden averaging 0.025 grams recoverable Au/ton.

Scenario A: If overburden is three meters thick and six sluices each capable of processing 100 tons of sediment per day work a 1 hectare pit, the project represents 180 days of work for 282 ounces of gold. Profit before operation cost is \$261/sluice/day @ \$1000/ozt and effective gold grade is 0.081 grams Au/ton.

Scenario B: If overburden is six meters thick and the same sluices are used, the project represents 315 days of work for 347 ounces of gold. Profit before operating cost is \$184/sluice/day, and the effective gold grade is 0.057 grams Au/ton. In this scenario gold recovery is 30% lower, meaning miner earnings are also 30% lower.



**Photo Panel 5. Panoramic of a large pit being worked by 4 sluices in Galangan.**

Similarly, this problem degrades fresh ore bodies when these fresh areas are overlain by tailings. As pit sediments are processed, tailings spread out as large fan shaped piles which become many meters thick. As a result of this unorganized approach a significant portion of ore layers are never exploited because miners abandon areas when tailing piles interfere with pit expansion or new pit development.

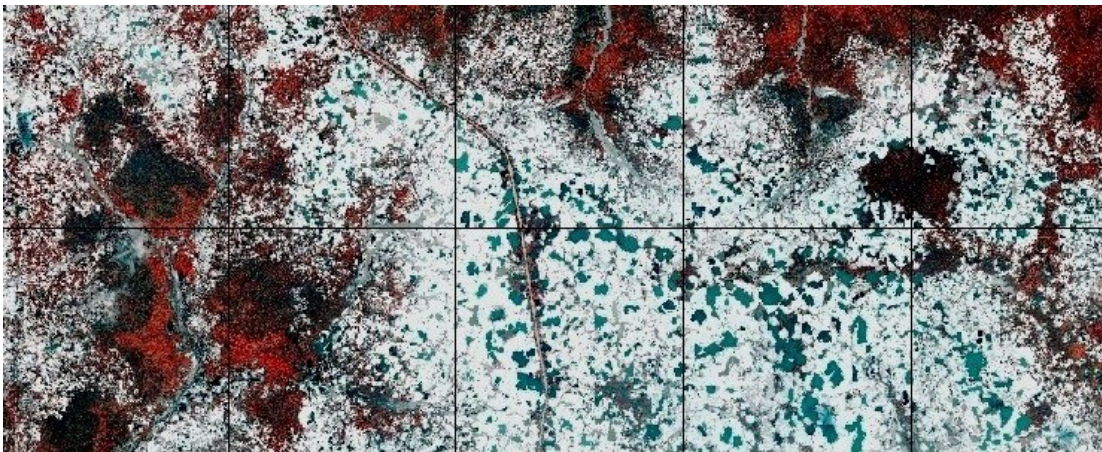


**Photo Panel 6. Due to a lack of pit planning, tailing overburden from previous workings decrease the ore grade (averaged recoverable grade) of pit sediments being processed.**

In aerial photos and in high resolution satellite images of the Galangan mine fields collected in August of 2006 a large proportion of mine pits are filled with water (photo panels 7 and 8). This is a common disturbance to the miners during high precipitation months effectively limiting activities.



**Photo Panel 7. Aerial photograph of mine pits filled with water; Galangan 2006.**



**Photo Panel 8. Satellite image depicting a portion of the Galangan mine fields (false color Quickbird™ high resolution satellite image). Most of the pits are filled with water due to seasonally high rainfall. The pit management problem can be seen in this image, as tailing sediments are spread out far beyond pit edges.**

Comparison of satellite data (Photo panel 8) with aerial photographs (Photo panel 7) was used by Telmer and Stapper (2007) to estimate the number of pits being operated, and the area of unexploited ground left within the mine fields. The amount of unexploited ore within a 6,500 hectare subregion inside the Galangan mine fields was estimated based on relatively well constraining data including (i) the area of affected but not exploited ground (no pits or signs of past pit infilling); (ii) average ore grade and

thickness of ore bearing sediments; and (iii) losses due to inefficient processing (it is estimated that sluicing captures only 60-80% of the gold). The analysis predicted that between 50 and 75% of the gold remains left behind in the exposed mine fields (Telmer and Stapper 2007).

### **Mercury use (Galangan)**

At the end of each day of work, sluice box carpets are cleaned with soap and water to collect 10-20kg of heavy mineral concentrate. In a bucket or large miner pan 150-500 grams of mercury is added to the concentrate from a plastic bottle and stirred into the sediments for five to ten minutes (Photo panel 9). During this time the mercury forms an amalgam with free gold particles.



**Photo Panel 9. (left) Mercury dealer providing mercury; and (right) miner washing concentrate with mercury to amalgamate the gold.**

After stirring, the pregnant mercury (containing gold) is separated from the concentrate by panning. Next this mercury is filtered through a cloth or t-shirt to separate amalgam (mercury and gold) from the residual liquid mercury. Mercury that is squeezed through the cloth filter is collected, and the amalgam left behind in the cloth filter is squeezed to form a ball of amalgam which is squeezed to remove as much mercury as possible. Silver colored amalgam balls weighing 5 to 20 grams are 0.5 - 2cm in diameter.

Amalgam balls are heated in the field or in gold shops to evaporate mercury from the amalgam. This produces a porous gold product called sponge gold, with vacuoles left by the evacuated mercury space. Sponge gold is typically 80-90% pure, with small amounts of mercury and other metals remaining. Amalgam burning is a service provided at no charge by gold shops in town, in exchange for customer loyalty. However, miners often prefer to burn it themselves because this is easy to do and it allows them to immediately see how much gold has been collected by their work.



**Photo Panel 10. (left) Miners carefully recover the pregnant mercury containing gold; (right) Amalgam ball resulting from squeezing pregnant mercury through a cloth filter.**

### **Amalgam composition (Galangan)**

An experiment was done to determine the composition of amalgam, with the help of gold shop operators in Kereng Pangsi. Two un-burned amalgam balls weighed at 27.9 grams and 33.9 grams, respectively. After the amalgam had been heated, the respective pieces of sponge-gold weighed 13.1 and 17.2 grams (see photo panel 11). Therefore the amalgam balls were 53% and 49% mercury by mass, confirming that amalgam in this context has a mass ratio of approximately 1:1 gold and mercury. Miners watch gold shop operators during the amalgam heating, and are paid for their gold based on the weight of the sponge gold. On this day, the gold was sold by the miners for 93% of the SPOT (international) gold price, which both buyer and seller can check independently by sending an SMS message (“gold”) to #6789 on their cell phones. The price at the time of

the experiment was 280,500 IDR per gram (960 CAD per ounce). In most of the gold shops in Kereng Pangsi and across the province, operators weigh the sponge gold in air and water. The difference is applied to an empirically based formula providing a density based assay method (determining sponge gold purity) to determine the buying price.



**Photo Panel 11. (left) Amalgam is weighted in a Kereng Pangsi gold shop before it is heated by blow torch to remove mercury; and (right) the sponge gold is weighed.**

### **Mercury use and behavior (Galangan)**

In Galangan and elsewhere, mercury use is influenced by entrenched behaviors and its use serves both practical functions (getting the gold) and less obvious functions (facilitating transactions) in the ASGM economy.

Security around many of the Galangan mining operations is facilitated by mercury dealers. These men provide a line of communication between parties by checking in on operations once a day. They provide mercury to the miners for amalgamation at no cash cost, but collect the residual mercury, which contains a small amount of fine gold not yet recovered by filtering. In this way the mercury dealers collect a tax for services provided. Later, this mercury is put on ice to lower the solubility of gold in the solution (mercury + gold), and filtered again. Alternatively the mercury can be distilled using a retort which leaves the gold behind.

In some cases mercury dealers supervise amalgamation and dictate how much mercury is used. Imposing the use of larger amounts of mercury favours the mercury dealer because more gold is returned to the mercury dealer. When dictated by a mercury dealer, the observed ratio of mercury used to gold was between 50:1 and 100:1. This should not be confused with mercury consumed; as most of this mercury is re-captured during amalgamation. For example, the amalgamator uses between 250 and 500 grams of mercury to produce a 10 gram ball of amalgam containing 5 grams gold.

### **Co-operative mine operations (Galangan)**

In addition to numerous separate mine operations, two mining co-operatives (locally called “ko-operasi”) were also visited along outskirts of the mine fields. These co-operatives were recent establishments (<3 years), and situated in newly cleared areas cut into surrounding jungle. Areas were established through a traditional land claiming system intended for entrepreneurs who are indigenous to the area. Inside, several teams of miners operate under the authority of the head land claimant (in spite of being called co-operatives, the head land claimant is the boss). Buildings are constructed on the property and shops, chicken coops and pool halls are setup to serve the miners. Mercury is provided by the land claimant and administered by team bosses. Small pools lined with plastic are constructed for amalgamation near the community center. Smaller amounts of mercury were used during amalgamation at these camps. Miners used between 125 and 250 grams on 10kg of concentrates to produce a 10 gram piece of amalgam. Thus the ratio of mercury used to gold was between 25:1 and 50:1 – roughly half the amount used under the supervision of mercury dealers (mercury used not to be confused with mercury consumed, as much of this mercury is re-captured during amalgamation).

Buried alluvial pit mines surveyed elsewhere in the province have numerous similarities to elements of the Galangan ASGM mine fields explained in this section. For this reason descriptions of additional areas surveyed become increasingly brief, but are included

with photos and captions in order to provide a written record of representative information and data from the survey.

### **Pojon (Kapuas River Basin), regency of Kapuas**

Pojon is a remote village on the Kapuas River similar in size and character to Kereng Pangi, with a population of around 5000. The town is difficult to access by road and for this reason transport of goods and miners is predominantly by boat via the city of Kuala Kapuas, 200km to the south.

In the vicinity of Pojon alluvial pit mining is widespread along tributaries flowing into the Kapuas River on its western banks. Radar imagery from 1999 reveals that intensive mining of these tributaries preceded that year (Telmer and Stapper 2007). During the field survey, maturity of the mining economy around Pojon was evidenced by the active marketing of ASGM mining real-estate (see Photo Panel 12).



**Photo Panel 12. Mine real-estate near Pojon. The cost of working (not owning) this 25 hectare location, was set at 282 million IDR (approx. 30,000 CAD\$).**

Ores being exploited around Pojon are similar to those at Galangan, and pits are operated in the same way. At three operations visited near to Pojon, ventures were co-owned and run as two man partnerships, with additional men employed. Operations visited are explained using photo panel 13-20, and accompanying captions.



Photo Panel 13. Sluice boxes are used for primary concentration, resulting in large tailing piles.



Photo Panel 14. (left) Miners working in the pit; (right) A partially filled abandoned pit.



Photo Panel 15. At the end of the day carpets are carefully collected and washed to recover the concentrate.



**Photo Panel 16. Mercury is sold in small 100g plastic bottles by gold shops in Pojon for 100,000Rp (approximately 10 dollars; so roughly \$100/kg – triple the international mercury price at the time).**



**Photo Panel 17. (left) Mercury is mixed into the concentrate to amalgamate gold; (right) the pregnant mercury is carefully recovered.**



**Photo Panel 18. (left) Pregnant mercury is filtered using the miners t-shirt; (right) Amalgam is filtered a second time using a plastic bag. Using this novel approach the miner was able to squeeze the amalgam very tightly, forcing tiny mercury droplets through pores in the thin plastic therefore reducing mercury consumption.**



**Photo Panel 19. The ball of amalgam is taken to a gold shop where it is heated by the shop operator using a torch, and then weighed and purchased by the shop operator.**



**Photo Panel 20.** In the Pojon area, detrital platinum is also collected by miners in this area. Miners refer to this placer platinum as “emas putih” (white gold). It is panned from the concentrates after amalgamation for gold. In this way mercury is used to separate platinum from gold because it does not amalgamate platinum under standard conditions.

#### **Tangar (Sampit River Basin), regency of Kotawaringin Timur**

In the Sampit River basin west of the port city of Sampit, pit mining was active in several areas. Four pit operations were visited near the town of Tangar. These operations were focused on buried terrace sediments approximately 15km west of the Sampit River channel.



**Photo Panel 21.** Teams of miners working near to the village of Tangar. Pits were being dug through 1m of soil to access mineralized sandy quartz pebble layers.

Quartz pebble clasts in the Tangar area were significantly smaller and less rounded than those of the Katingan River basin (Galangan mine fields), suggesting differing

sedimentary histories. Soil horizons in this area were not as pronounced as elsewhere but organic, a hummus rich sandy horizon, and a grey elluviated horizon were evident. Below the soil, brown sandy sediments intercalated with quartz pebbles, and clay lenses constituted the mineralized layer being targeted. The depth of the mineralized layer is only 1-2 meters thick, and is underlain by hard clay.

A few hundred meters distant from the sandy pits shown in Photo Panel 20 a different group of miners were working an extension of the same ore body, but using rafts to do so in a location overlain by wetland muck. Sluicing at this site was mobilizing huge volumes of dark organic-rich matter into suspension creating a dark coloured organic slurry which entered directly into local streams (Photo panel 22). Sampled stream water one kilometre downstream of this operation had high TSS (1295mg/L), with mercury concentration per litre water of 1.1µg/L. This stream had highest total mercury relative to all waters sampled throughout the campaign. The high mercury level is attributed to Hg-rich particulate organic matter (POM) in suspension – see photo panel #22.



**Photo Panel 22. Miners working in a wetland area near Tangar. Note the dark water colour resulting from organic detritus, high POM and mud in suspension.**

Based on visits to four operations, gold mining in the vicinity of Tangar was less lucrative than mining areas surveyed in adjacent regencies. The miners encountered were young men from Java and generally lacked the level of expertise, organization and mining knowledge observed elsewhere (see Photo Panel 22 for example).



**Photo Panel 23. A lack of health knowledge is shown in this photograph of a miner showing his son how amalgam is heated to remove mercury. He is not aware of the toxicity to himself and the even greater danger to his son.**

#### **Hamputung River basin (Kahayan River basin), regency of Gunung Mas**

The Hamputung river basin is a small upland catchment of the Kahayan river basin. In addition to mining of stream and channel gravels and their banks, pit mining was also surveyed. Pits are dug to exploit sediments from areas immediately adjacent to stream channels, to upslope areas 500 meters from the active channels. Soils in the upland basin can be generally classified as ferric Acrisols with high iron levels, and clay horizons below. Gold is particularly concentrated in soil horizons above clay lenses, suggesting mobilization of gold particles from overlying soil layers.



**Photo Panel 24. Pit operations being worked near the village of Ponyoi, in the upper Kahayan Basin. (left) This pit is 2-3 meters deep; (right) A transition between horizons, in which gold is concentrated above a clay horizon, is pointed out by the mine boss.**



**Photo Panel 25. (left) Sluce carpets are washed at the end of the day; (right) Concentrate was panned to clean the gold, and no mercury was used. One day of operation by two miners at this small pit (Photo panels 24 and 25) produced more than seven grams of gold.**



**Photo Panel 26. Miners use water jets to dig pits into fine sandy sediments directly adjacent to stream channels in the Hamputung River basin (headwaters of the Kahayan River).**

#### **2.3.4 Alluvial placers**

Alluvial miners also operate using sluice boxes and diesel motors, but they also use tools designed specifically for digging into and exploiting riverbed sediments. Suction hoses are fit with steel spades which are firmly attached to long wooden poles. These poles allow teams of miners working in unison to control the position and digging motion of the suction hose delivering sediments to the miners raft (dredge).

On most river dredges, sluice boxes are tiered (built with a *zigzag* design). In this design, two sluices are inclined towards one another so that slurry drops from one to the other, changing direction as it does. These sluices are wider and shorter than pit sluices in order to utilize raft space efficiently. Tailings run off into the river from the lower sluice and fine sediments remain in suspension for large distances downstream of mining activities. In this section several alluvial mining operations that were surveyed are described, including photographs and captions.

#### **Kalanaman River (Katingan River basin), Katingan Regency**

Alluvial gold mining was also visited on the Kalanaman River between Kereng Pangi and Tumbang Samba (near Galangan). Most of the dredge miners in this area are indigenous Dayaks. On the Kalanaman River miners were observed breaking apart thick clays which surround gold bearing gravels. To do this, teams of miners worked together to operate

long poles lashed to digging spades with suction hoses. Ropes attached to the suction device were being used for lifting the unit to the surface with a foot operated pulley system (Photo panel 28). In addition to a spade, the end of the suction device is outfit with a high pressure hose (jet) which facilitates blasting the excavated sediment apart in advance of being sucked through the main pipe. This approach helps to liberate sediment and acts like a drill. Due to clay content of the sediments being exploited, siltation was extremely high around these operations.

River miners on the Kalanaman use mercury for amalgamation along the river bank at the end of each work shift (Photo panel 29). Mercury becomes *dirty* with successive uses due to oxidation reducing its effectiveness for additional amalgamation cycles. For this reason it has previously been reported that river miners in this area dispose of their used mercury directly into the river. This behaviour was not observed during the survey and miners denied disposing of mercury in this way.



**Photo Panel 27. Trees are cut to make space for dredges rafted along the Kalanaman River.**



**Photo Panel 28. (left) Teams of young miners work together to dig into clay-rich river banks. (right) Pulley system acts as a hoist for the heavy suction apparatus, and is powered by miners with their legs.**



**Photo Panel 29. (left) Sediment and water slurry is pumped up to the top of the sluice box (right). Mercury is used to amalgamate concentrate on the river bank.**

### **Kapuas River Basin, Kapuas Regency**

Extreme sedimentation resulting from mining activities was also observed on tributaries of the Kapuas River. The following photo panels and captions are used to present survey results. No active mining operations were found on the Kapuas River upstream of Pojon

for 15km, the extent travelled by boat. According to the guide, miners must have been operating further upstream to the north.



**Photo Panel 30. (left) Pristine stream conditions in the Kapuas River basin from small airplane; (right) Tea colored water low in TSS (3.8mg/L) but rich in humic acids.**



**Photo Panel 31. (left) River mining operations and sedimentation on the Muro River, a large tributary of the Kapuas photographed from the air; (right) Empty fuel barrels are barged downstream on the Muro River, after delivering diesel fuel to mine operators upstream.**



**Photo Panel 32. Sedimentation of small tributaries that flow into the Kapuas River from the west, near Pojon. Contrast these photographs with the pristine drainage in Photo panel 30.**



**Photo Panel 33. (left) Dredges connected to one another in the Kapuas river, 45km upstream of Pojon; (right) Dredge mining supplies being sold at roadside shops in the town of Pojon.**

### **Kahayan River, regency of Gunung Mas**

River dredges have operated on the Kahayan River for many years. It may be the river most affected by mining in Central Kalimantan. During this survey, dredges were counted along the Kahayan River while traveling upstream from Palangkaraya by boat. Between Palangkaraya and Kuala Kurun, active mining activities were confined to a few

tributaries near to Kuala Kurun. Between Kuala Kurun and the town of Hamputung (approximately 100km) ninety two dredges were counted of which 28 were in operating condition. The state of most of the dredges suggested that river mining had decreased over recent years.

Upstream of Tanbung Miri, three watersheds of roughly equal size comprise headwaters of the Kahayan River basin. These are the Miri River, the Hamputung River and the (Upper) Kahayan River. ASGM is active in each of these basins.



**Photo Panel 34. A mine site along the Kahayan River channel where the river levee had been dredged (rafted operators). Note the original levee bank at image left; the excavated mass of sediment (mostly sand) at this site alone is estimated to be 60,000 tonnes, most of which has subsequently been transported down the Kahayan.**

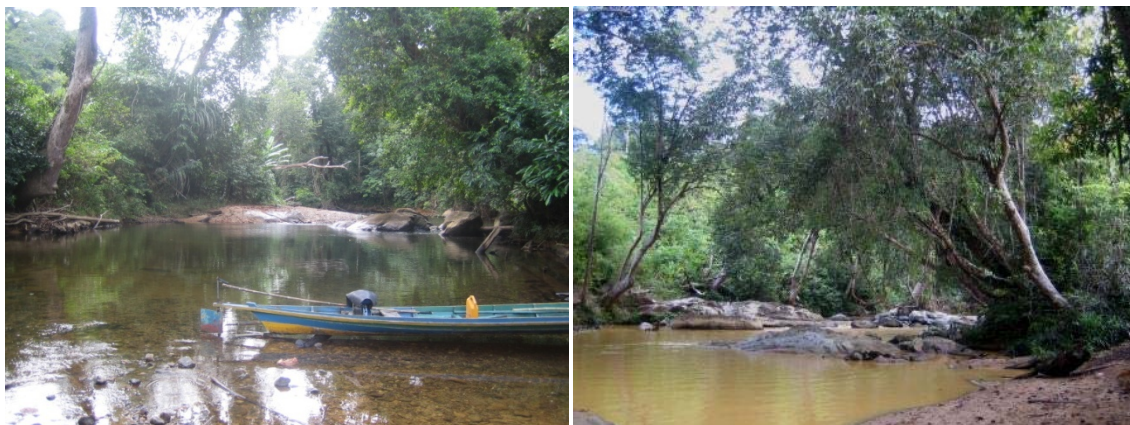
Upstream of Hamputung, at the juncture of the Kahayan River and Hamputung Rivers, the Hamputung River tributary was traveled north for 20km to the village of Ponyoi. Watersheds in these hilly terrains are less than 100km<sup>2</sup>, and tributaries surge dramatically during heavy rain storms. With the help of local guides, several mining operations operated by Dayak (indigenous) miners were surveyed near Ponyoi. Below, photo panels with captions are used to describe what was surveyed.



**Photo Panel 35. (left) 5 kilometers upstream of Ponyoi, after numerous forks in the river, the stream shallows; (right) Plastic battons were setup on these sluice boxes floated by timbers, to prevent pebbles from knocking gold off the carpets.**



**Photo Panel 36. (left) Miners liberate sediments with their feet while controlling the suction pump (which is under the water) with a throttle-chord; (right) Miners operate small floating sluice boxes directly in stream channels.**



**Photo Panel 37. (left) A clear water pool early in the day before mining commenced below rapids on the Kahungoi River; (right) the same pool late in the afternoon after several hours of mining upstream of the rapids. A study of sediment mobilization by these operations is presented in Chapter 3.**

In the Hamputung River basin mercury use was not observed in situ by miners in upper parts of the Kahayan River basin. Instead, miners simply panned their concentrates and later sold them to gold shops in Tambung Miri, Tewah and Kuala Kurun. It was at these gold shops (visited in Tambung Miri and Kuala Kurun) that mercury was being used for amalgamation. Shop operators first weighed the concentrate, then amalgamated it, and afterwards weighed the residual concentrate. The difference is the amount of gold amalgamated and miners were being paid on this basis. In this scenario mercury-use facilitated the gold transaction process. Though familiar with retorts, the gold shops visited (only 2) were not aware of or using mercury capture technologies such as retorts or fumehood mercury capture systems (see Chapter 4).

#### **Barito River near Tambung Kunyi, regency of Murung Raya**

As part of the survey, the Barito River was travelled north by boat from Puruk Cahu to Tambung Kunyi (approximately 50km). The amount of active river mining increased dramatically upstream of Tambung Kunyi. In this area, river dredges being used were much larger than those seen in adjacent rivers basins. Dredges were being kept in place amidst strong river currents using long thick ropes which connect the dredges to large trees on each shore, posing hazards for boat navigation. Modified automotive engines

were being used to suck river gravels up from depths of up to ten meters. Pressure jets were not being used because sediments being exploited were river gravels with very little fines. As a result, less siltation results from these operations.

Diesel and engine maintenance are the main operating costs. In Tambung Kunyi the street cost of diesel was 16,000Rp/L (\$1.75CDN /L) in July, 2008. Operators manage shifts around 200 liter barrels of diesel brought upriver by boat. Barring complications, 200 liters of diesel can operate a large dredge for 2-3 days if run for long shifts, which is typical. Gold recoveries vary, but five grams of gold per day is required just to cover diesel costs. Ten to twenty grams is common and up to 30 grams per day is possible but only when the river is low and concentrated zones are found to exploit. Workers operating these dredges were young men who had travelled up river by boat from Banjarmasin, a trip of more than 400km that takes 2-5 days.



**Photo Panel 38. Large dredges on the Barito River held in place using long thick ropes**



**Photo Panel 39. (left) Miners control the suction hose by manipulating a long wooden pole lashed to the suction pipe apparatus; (right) The large nozzle of the suction apparatus is not sharp like those on other rivers, because loose gravels are being sucked from the river bed.**



**Photo Panel 40. Foot operated wooden pulley system used to lower and lift the heavy suction apparatus from a shaded bench on the dredge.**



**Photo Panel 41. (left) A large converted automobile engine was used to pump sediments up to the dredge on the Barito River. (right) Larger motors enable greater slurry through-put on the Barito River dredges.**

### **2.3.5 Hydrothermal lode gold**

Hard rock ores are mined from outcrops in northern parts of the Barito and Kahayan river basins, and presumably elsewhere. Vein associated rocks are mined, then crushed and transported prior to treatment using mercury and eventually cyanide.

This portion of the survey is biased to a single ASGM region because additional hard rock operations were not visited. During the survey, however, evidence of other hard rock gold mining operations was encountered.

#### **Mount Muro (Upper Barito River), regency of Murung Raya**

On the Barito River near the city of Puruk Cahu mining of both hard rock ores (epithermal quartz vein hosted gold) and alluvial placers (placers formed proximal to primary gold deposits by weathering) have been active since the early 1970's (Manaf 1999). After extensive exploration investment in the early 1980s, a thirty year contract of work (COW) was granted to PT. Indo Muro Kencana by the Indonesian government in 1985. A third generation version of this agreement is still in effect, and covers 47,940 hectares. Despite numerous instances of conflict with local small-scale miners, more than one million ounces of gold were extracted from the COW between 1995 and 2000. During the survey, Straits Resources Inc. were the COW holder and continued mining

from open pits in the concession while artisanal miners were also collecting and processing ores at multiple locations within the COW, including in abandoned open pits. Large scale mining at the Gunung Baruh open pit was decommissioned in 2002, but small-scale miners have continued to dig into the exposed Kerikil gold veins to exploit ore. During the survey, an encampment of miners living on the benches of the abandoned mine site was visited. A description of the mining operations is provided in the photo panels and captions which follow.



**Photo Panel 42. (left) Abandoned Gunung Baru LSM mine site (Kerikil veins, Mount Muro), with settlements of small-scale miners living and working on mine steps; (right) Hoist above the open shaft entrance, where the Kerikil vein has been mined.**



**Photo Panel 43. Miners descend into the open shaft for a five hour shift with head lamps, hammers and bags. In 2006 a co-worker of the miners died in this shaft from a fall.**



**Photo Panel 44. (left) Ore that is brought to the surface is hammered into small pieces with a sledge hammer; (right) Crushed ore is bagged in 40kg sacs and transported to a nearby trammel-mill circuit for processing.**

Most of the ore mined in the vicinity of Mount Muro is processed adjacent to the village of Mangkuhoi in trammel-mill sheds that have been active for more than twenty years. Inside each trammel-mill shed are eight to twelve 40 gallon (150 litre) steel drums in circuits powered by diesel motors. A diesel motor is used to turn a central wooden shaft flanked by trammel mills on each side. Power is transferred to the shaft and then from the shaft to the mills by large rubber belts made from old tires. After ore was added to

each drum in the circuit, steel bars (70cm x 12cm in diameter), water, and mercury were added before each was sealed. Between one and four kilograms of mercury was added to each trammel, depending on the ore being processed. These are huge amounts of mercury, even by whole-ore-amalgamation standards.



**Photo Panel 45.** Large sheds in the village of Mangkuhoi contain trammel-mill circuits composed of 6 to 12 individual mills turned by large rubber belts. The large fuel-barrel chimney is intended to reduce exposure to mercury fumes during the heating of amalgam.



**Photo Panel 46.** Trammel mills are rinsed with water to be cleaned, with care to collect as much mercury as possible. Steels bars in the foreground are put inside the steel drums and act as the grinding media.

At Mount Muro, huge volumes of mercury are used because the ores are rich in silver, containing between 10 and 20 parts silver for each part gold. In order to amalgamate all of the gold, the silver must also be amalgamated. Making matters worse, silver forms a less efficient amalgam than gold, requiring 3 parts mercury for each part silver. For this reason, excessive amounts of mercury have and continue to be used by ASGM around Mount Muro. The location is undeniably a significant regional mercury emission source, and may in fact be one of the largest ASGM mercury emission sources on the planet.

Trammel circuits are run for one to three days during which individual trammels are disconnected and opened to check the mercury. When amalgamation is complete, the crushed ore is placed aside, and mercury is poured from the trammels into large bowls. The mercury is filtered through bath towels, forming fist sized balls of amalgam. Mercury that passes through the towels is used again but will be less effective, due to oxidization and contamination. Miners are aware of this but were unfamiliar with techniques to reactivate their mercury during the survey and thus were not doing so. The Panjoja process used to re-activate mercury, described in Chapter 4, is useful in this context.



**Photo Panel 47. (left) Large stainless steel bowls are used to collect the pregnant mercury; (right) This mercury is filtered through towels to separate the amalgam from residual liquid mercury which will re-enter the circuit. The amalgam is principally mercury, silver, and gold.**

The amalgam produced is roughly 80% mercury, 18% silver and 2% gold. Based on these ratios and using 2008 values (mercury 25 CAD/kg; silver 15 CAD/ozt; gold 850 CAD/ozt),

one kilogram of amalgam therefore contained roughly \$20 mercury, \$85 silver and \$550 gold. At printing time of this thesis (fall 2011) the price of each of these metals had more than doubled from these 2008 values.

To separate gold and silver from the mercury the amalgam is heated. Between one and fifty kilograms of amalgam are processed at a time, depending on the scale of collaboration between miners and the time between processing - factors which relate to the equipment being used and the urgency for return on labour and capital. Amalgam is heated inside large steel retorts which are used to recover an initial fraction of mercury which melts from amalgam and is poured off as a liquid, as the retort begins to warm. Retorts of this type capture an estimated 25-50% of the mercury, but tests were not made to confirm this estimate. After this stage, the large retorts are placed below chimneys made from 90 gallon (340L) fuel barrels stacked upright, reaching heights of 10 to 15 meters (see Photo panel 45). Over a wood fire, steel pots containing amalgam are heated sending vast quantities of concentrated mercury vapour up the chimneys. The result is a doré of silver and gold, with smaller amounts of mercury and other impurities.



**Photo Panel 48. (left) Fist size ball of amalgam weighing 4.5kg; (right) Once mercury has been volatilized from the amalgam, what remains is a heavy metal slab called doré. The content of this doré is 8 parts silver and 2 parts gold, but still contains impurities including mercury, copper and lead.**

In a final processing stage, the doré is purified into 24 Karat gold (99.5% pure) by a method called “quartering”. First the doré is boiled in nitric acid which dissolves all metals except gold. At this stage silver is added to the gold at a ratio of roughly 4 parts silver to 1 part gold, and they are heated together to form a molten alloy. Gas or oxy-acetylene torches are used to do this in clay crucibles and the alloy is poured into water to create a gravel with high surface area (Photo panel 49). The alloy is boiled in nitric acid once more, dissolving impurities into the nitric solution, leaving only gold behind (Photo panel 50). At this stage the gold is a brown-coloured colloidal mud resembling ground coffee. Finally it is smelted and poured, creating a 24K ingot or button (Photo panel 51). This product trades internationally at the London Stock price for gold.



**Photo Panel 49. (left) Molten alloy is poured into water to create a gravel with high surface area (shown at right).**



**Photo Panel 50.** The alloy gravel is put in steel bowls, covered in Nitric acid and boiled until the silver dissolves, leaving only pure gold behind, which resembles a brown mud.



**Photo Panel 51.** The gold is dried and smelted again to pour a 24K gold ingot or button.

### **Cyanide operations in the vicinity of Mount Muro, Regency of Murung Raya**

According to operation bosses in Puruk Cahu, expertise and equipment for processing hard rock ores with cyanide began coming from the Indonesian island of Sulawesi around 2005. Since 2006 tailings from the amalgamation circuits described above have been processed by a carbon-in-pulp (CIP) cyanide process. During the survey, miners reported that approximately ten tongs (large 30 tonne cyanide vats) were being operated in the location known as Portside, a few hundred meters from the Barito River. Tailings were being collected in nylon bags and transported by truck to this location for

cyanidation. In some cases entire trammel sheds were being disassembled to collect tailings which had collected around and below them over many years. The tailings contained innumerable tiny droplets of dispersed “floured” mercury, visible using a 5X optical lens. Two compound samples of these tailings were collected and analyzed for mercury content. Measured mercury concentrations were 846ppm±16% and 1,663ppm±18%.

Approximately 300 sacs weighing 20-25kg each, amounting to 5000-7500kg, were being emptied into each tong. Pre-cyanide tailing samples from two different tailing piles were collected and later fire assayed for gold and silver, and contained 20.6 and 23.5 grams per tonne gold. Both were over 300 grams per tonne silver. The tongs were filled with water, sodium cyanide, and calcium hydroxide (lime) which was being used to keep solution pH around 11. Slurry in the tong was agitated by a propeller, and air was being pumped into the tong using a compressor. Once the desired pH was reached 100kg of activated carbon was added, providing absorption sites for gold-cyanide, silver-cyanide, and mercury-cyanide compounds. After 24-36 hours, the tong was drained, and a metal screen was used to trap pregnant carbon. This carbon was burned into ash, which was smelted to recover the gold. According to operators roughly one ounce of gold was being recovered from each cycle, suggesting a recovery of 5-10 grams of gold per ton of tailings.

Two post-cyanide tailing samples collected and later assayed for gold and silver by fire assay had 1.01 and 6.06 grams per tonne gold; and 62 and 58 grams per tonne silver. Thus, it is clear that a significant amount of gold and silver remain in the tailings, even after the ores have been processed by whole ore amalgamation and then by CIP cyanidation. This is most likely due to poor gold liberation which could be improved with better crushing and milling, and inefficient process control during cyanidation.



**Photo Panel 52. (left) Tailings from whole-ore amalgamation bagged and moved by truck to a nearby property for CIP treatment. (right) Large agitated tanks called tongs used for carbon in pulp cyanide processing.**



**Photo Panel 53. (left) One of ten 30,000 litre tongs at the Portside site near Mount Muro in 2008. (right) Air compressor used to pump air into the tanks, delivering oxygen necessary for efficient cyanidation.**

### **2.3.6 Estimates of mercury use and fate in Central Kalimantan**

In this section, estimates of mercury use and emissions are presented for each type of mining in the province. The short-term fate of mercury is discussed for each context. Corresponding estimates of gold production and workforce size are also presented. All estimates have been triangulated using information from multiple lines of evidence

checked against each other (amount of gold produced verses amount of mercury used verses number of miners, etc).

### **Buried alluvial (pit-mined) gold**

It is estimated that in 2008, 5500 units (1 unit = 1 operating sluice box) operating across approximately 1500 pits in the regencies of Kotawaringin Barat, Seruyan, Kotawaringin Timur, Katingan, Gunung Mas, Kapuas, and Murung Raya consumed approximately 10 tons mercury to produce 7.5 tons gold (1.3 : 1 mercury to gold ratio). The workforce responsible is estimated to be 25,000 miners. These estimates are based on (a) visits to more than forty open pit sites (numerous pit operations at each) in the regencies of East Kotawaringin, Katingan, Kapuas, and Gunung Mas; (b) discussions with miners and gold shop owners in these regencies; and (c) mapping of ASGM scars using satellite imagery (Telmer and Stapper, 2007).

Mercury used for recovering pit-mined alluvial gold is principally lost as vapor when amalgam is heated at mine sites and at gold shops. Seven and a half tonnes of mercury – an amount equivalent to the mass of gold produced, is emitted this way. A smaller amount of mercury (2.5 tonnes or 25% of total) is lost to concentrates and panning pools during amalgamation. Sometimes concentrates are reprocessed to remove zircons and recover additional gold, providing an opportunity to recover a portion of this mercury. Retorts and fumehoods can also be used to recover mercury during amalgam burning, but were not widely used by miners in the 2008 survey.

### **Alluvial (stream and river channel) mined gold**

In 2008 it is estimated that 1500-2000 dredges remained active for most of the year on the Kalanaman, Rungan, Kahayan, Muro, Kapuas and Barito rivers (and tributaries in these basins) while up to 3000 were active during the four driest months of the year. These activities used approximately 5.3 tons of mercury to produce 4.25 tons of gold. The workforce involved is estimated to be 15,000 miners. These estimates were made based on (i) dredge counts during river transit by boat on the Kalanaman, Kahayan and

Barito rivers; (ii) discussion with dredge miners and gold shop owners; (iii) dredge counts made from small-airplane over reaches of the Kahayan, Muro and Kapuas rivers by boat and small airplane during this survey; and (iv) geo-referenced photography taken from a chartered helicopter flight over the Katingan, Kahayan and Kapuas Rivers in 2006 (by Telmer).

River miners in the Kahayan and Barito river basins bring panned concentrates home or to gold shops where they are amalgamated. In these areas mercury emissions occur from homes and gold shops located in urban centers. Mercury emissions are roughly equal the amount of gold produced, 4.25 tonnes.

On the Kalanamaan River (in the Katingan River basin) and presumably on numerous other tributaries, miners use mercury in situ for amalgamation at rivers edge, and then bring amalgam to gold shops for sale. Because concentrates are panned with mercury during amalgamation, between 5 and 20 kilograms of contaminated heavy mineral concentrates are left at amalgamation sites each time. Approximately 1.3 tonnes (25%) of mercury used by river miners is deposited into stream sediments in this way.

#### **Hydrothermal lode gold (hard rock)**

Around Mount Muro in the Regency of Murung Raya at least 50 primary ore milling circuits consumed approximately 50 tons of mercury to produce 1.5 tons of gold and more than 10 tonnes of silver in 2008. The workforce directly involved is estimated to be 3000 individuals. This represents a conservative estimate for the region because additional hard-rock locations which function similar to Mount Muro are likely to exist, and would increase this estimate. The ratio of mercury used to gold produced at Mount Muro is estimated to be 33:1. These estimates are based on (a) visits to 14 trammel mill processing centers in the vicinity of Mount Muro; (b) discussions with refiners, bosses and gold shops owners in the area; and (c) data from a follow-up assessment made by Telmer in 2010.

Half of the mercury used for whole ore amalgamation (hard-rock mining) in the vicinity of Mount Muro (approximately twenty-five tonnes) is evaporated during the heating of amalgam. A portion of this emission is re-deposited locally while another portion is transported long distances. An additional twenty-five tonnes is lost to tailings. Mercury droplets were visible in tailings before and after they are processed with cyanide, suggesting volatilization likely occurs before and after cyanide treatment. Floured mercury from the trammel mills is easily suspended in water. As a result, precipitation and overland flow are pathways of this mercury into stream and river networks.

Mercury forms soluble complexes with cyanide. These reactions occur more slowly than cyanide-gold complexes, however, and therefore post-cyanide tailings remain high in mercury. The residual cyanide/mercury reactions are not well understood. It can be hypothesized that the breakdown of cyano-mercury complexes releases mercury as gaseous elemental mercury, which could be expected to volatilize from neutralizing water. The volatilization of gaseous mercury from heap cyanide leaching operations in Nevada has been measured concurrently with measurements of cyanide degrading (Eckley, Gustin et al. 2010) (Gustin, Coolbaugh et al. 2003) – work that suggests rates of mercury volatilization from cyanide effluent and tailing dumps in the vicinity of Mount Muro may be very high. More research is needed to study these reactions, and how they affect mercury bio-availability.

This chapter has only presented a cursory discussion of ASGM mercury pathways and fate. This complex subject area requires further research, as many gaps in understanding remain.

### **Un-visited ASGM operations**

Central Kalimantan government webpages list regencies and sub-districts known to possess gold mineralization and mining activities. In addition to the districts surveyed, the list includes West Kotawaringin (regency), East Barito (regency), South Barito (regency), Northern Suruyan (subdistrict), and Northern Katingan (subdistrict). ASGM activities have been confirmed in all of these districts using satellite imagery (Telmer

and Stapper 2007), a detection approach heavily biased towards pit operations. No information is available from which to estimate the extent of river and/or hard-rock mining in these areas. Likewise, there is evidence that hard rock ASGM operations operate in northern parts of the Kahayan and Katingan river basins, but these operations have not been surveyed and therefore are not presumed in the ASGM and mercury use estimates made in the following section. Therefore the estimates made in this chapter are conservative.

### **2.3.7 Total mercury emissions from ASGM in Central Kalimantan**

It is estimated that 13.25 tonnes of gold was produced using 65.3 tonnes of mercury in the province of Central Kalimantan in 2008. A disproportional amount of this mercury (around 50 tonnes) was used by whole-ore amalgamation operations in the Regency of Murung Raya. These operations represent 77% of mercury use in the province, but are responsible for only 11% of the gold produced. It may be that unvisited (additional) hard-rock operations where whole-ore amalgamation is practiced would increase this estimate further. ASGM is also widespread in the provinces of East Kalimantan, and West Kalimantan, but no effort is made to quantify these activities in this thesis.

### **2.3.8 Assessment of the ASGM gold sector in Central Kalimantan**

Approximately 43,000 small-scale gold miners in Central Kalimantan produced an estimated 13.25 tons of gold in 2008 (426,045 troy ounces) worth approximately 362 million CAD based on 2008 prices (\$850 CAD/ozt). Split evenly (which it is not) this represents 31 dollars per day per worker, based on 260 work days per year. If amalgamated with Central Kalimantan's Regional Gross Domestic Product (RGDP) statistics for 2008, ASGM contributes 9% of provincial RGDP. If incorporated with mining and quarrying figures, based on sector contribution in 2006 for which mining and quarrying contributed 7% to RGDP, the mining sector represented nearer to 15% of RGDP. Several regency administration websites acknowledge that ASGM contributes significantly to the regional economy, while acknowledging that records do not exist for the sector.

ASGM gross product (362 million dollars) can be compared with production figures from the Mount Muro large scale mine, operated by Straits Resources Ltd. in 2008. Expected production in 2008 was 80,000ozt gold (worth 68 million CAD in 2008 prices) and 800,000ozt silver (14.4 million CAD). Regarding gross gold production, therefore, this large scale operation produced approximately one quarter of provincial ASGM gold production in 2008.

The size and extent of remaining ASGM reserves in the province depends to a large degree on the grade necessary for operations to be profitable. Most economists believe the international gold prices will remain high relative to other commodities, for numerous reasons. In this context, low grade deposits are likely to remain economic for small scale operations. Across much of Kalimantan, access to mining areas is a major factor limiting exploitation. As the provinces' transportation infrastructure improves, new areas will be found and exploited.

A simplistic ore deposit model can be constructed based on mining operations visited in this survey and comparisons between aerial photography and satellite images (Telmer and Stapper 2007). Using this approach, it is estimated that minimally another 40,000 hectares of ground across the province is likely to possess viable low-grade alluvial ores similar to those already exploited. If this is true, there would be approximately 378 tons of gold remaining in this resource alone and at the 2008 rate of small-scale pit mining these reserves would last 54 years. This is a simplified model, but presents a practical message and can serve as a conceptual model to be refined.

The likelihood of future LSM gold projects in Central Kalimantan is strong. More than thirty companies are actively exploring and at least three have reached the feasibility study phase. The likelihood for future LSGM-ASGM contact and conflict is high. Future relations will depend to a large extent on how the provincial and regency governments approach, and develop the sector in forthcoming years.

## 2.4 Chapter summary

In 2008, the small-scale gold mining sector in Central Kalimantan used approximately 65.3 tonnes of mercury to produce 13.25 tonnes of gold. Approximately 44% of this mercury (29 tonnes) was emitted to the atmosphere. The fate of this mercury is not well constrained – a fraction is re-deposited within local to regional distances from the emission source, and another fraction experiences long range transport. The remaining 66% (36 tonnes) was deposited with contaminated tailings, effluent, and soils around ASGM processing sites.

A disproportional amount of mercury use is consumed by whole-ore amalgamation operations in the Regency of Murung Raya. Mercury used in the vicinity of Mount Muro accounts for approximately 80% of provincial use, despite producing only 13% of the provinces' ASGM gold in 2008.

Collectively, ASGM mercury emissions are larger than any other natural landscape mercury flux. ASGM mercury emissions, therefore, represent a significant perturbation to the region's natural mercury system.

## **Chapter 3. River Sediment Study**

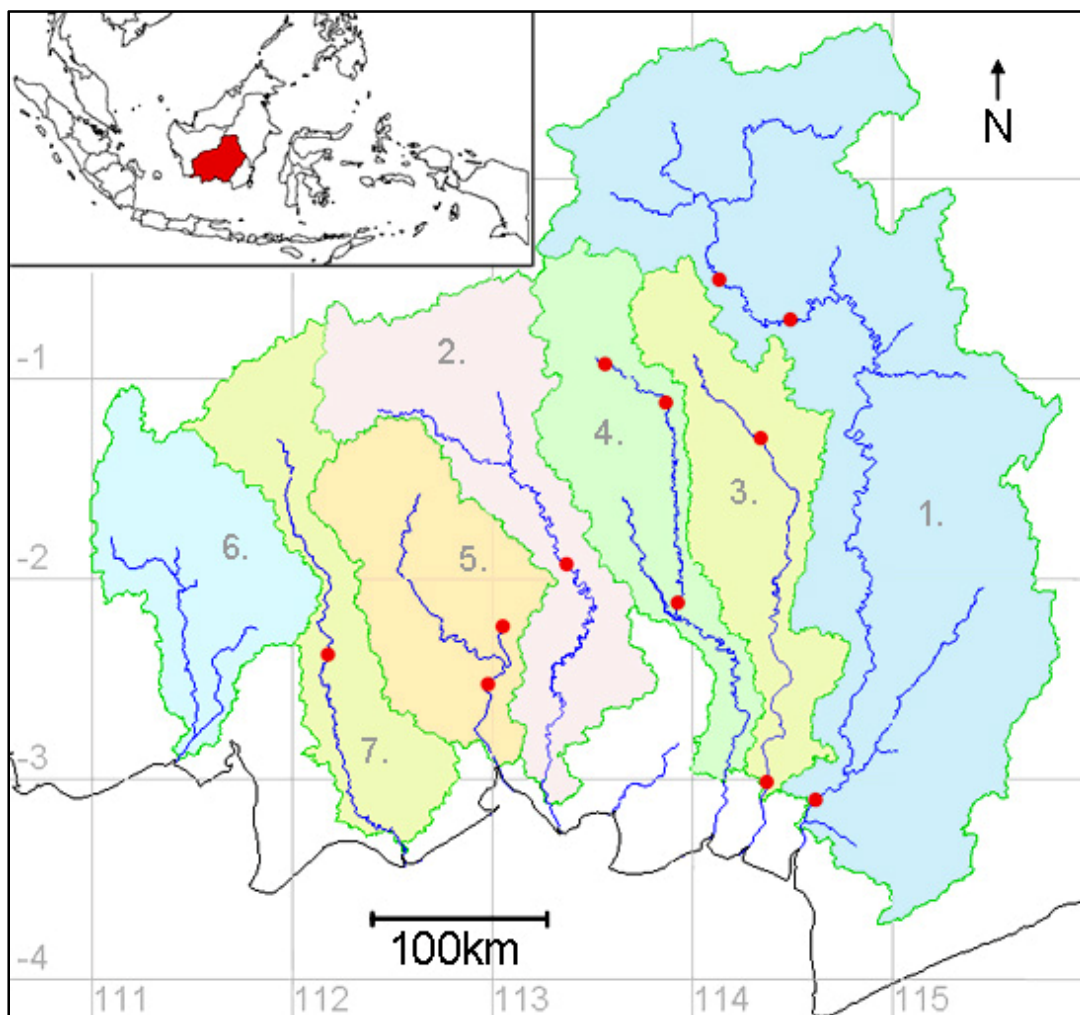
### **3.1 Introduction**

This chapter presents a study of river sediments, mercury transport, and the role of mercury from ASGM in the rivers of Central Kalimantan. The results are based on analysis of sediment and mercury in various media, study of ASGM communities as presented in Chapter 2, and hydrological modeling tools used to estimate annual fluxes of sediment and mercury in the province's rivers.

### **3.2 Methods**

#### **3.2.1 River water and sediment sampling**

Stream and river sediments were sampled at twenty nine locations across six of the provinces seven largest river basins. River (or stream) and sediment samples were collected in the regencies of Seruyan, Kotawaringin Timur, Katingan, Gunung Mas, Pulang Pisau, Kapuas, Murung Raya and the capital regency of Palangkaraya.



**Figure 9. Map of river sampling locations. Multiple sampling instances were conducted in the vicinity of several of the marked locations. Watershed boundaries were delineated using GIS software, from SRTM digital elevation data.**

Sampled sites include pristine waters upstream of ASGM activities, highly turbid sites directly affected by mining, acidic streams of peat-lands, and the region's large rivers. pH and alkalinity were measured in situ, using a handheld pH meter and manual digital titrator. River waters were collected using a custom travel-friendly version of a niskin bottle or wide-mouth teflon bottles, from dock or boat.

### **3.2.2 Bedload sediment sampling**

Twenty six bedload sediment samples were collected by wading into rivers and reaching upstream to grab samples from the bed wearing nitrile gloves. Samples were bagged and excess water was poured off. Bags were securely sealed and double bagged.

Contamination is a critical concern when making measurements of mercury in the environment. Special care must be taken in field situations where samples are likely to vary by orders of magnitude, as is the case when mine tailings are collected in proximity to unaffected sediments representing background concentrations. Special care was employed before, during and after-sampling to address these concerns including application of the clean hands approach and sample isolation, based on sampling standards outlined in US EPA method 1631 for the Determination of low level mercury in environmental media (US EPA, 1991).

### **3.2.3 Suspended sediment sampling for total suspended solids (TSS)**

At stream and river sampling sites, water samples were collected in duplicate using separate bottles. From each, collected water samples were filtered in situ for suspended sediment. Suspended sediments were trapped on pre-weighed Whatman GF/F Glass Microfibre 0.7 $\mu$ m filters. The Millipore Sterifil Aseptic System – a handheld filter unit, was used to pump sample water through the membranes. After a recorded volume of water was pumped through the membranes they were wicked of excess water on clean Whatman filter papers, folded using tweezers and placed inside small ziplock bags. In the lab filters were dried at 40°C and weighed on an analytical balance for analysis of TSS, and mercury content.

Suspended sediments were also filtered (in situ) using Polycarbonate Millipore Isopore GTTP Membrane 0.2 $\mu$ m filters for XRD analysis and optical analysis of grain-size. In the lab a Nikon Eclipse E200 microscope was used to visually estimate the mass contribution of various grain sizes.

### **3.2.4 Stratigraphic profile sediment samples**

During visits to mining operations, sediment horizons were sampled to determine regional mercury levels. A hand spade was used to expose and collect sediment from stratigraphic horizons apparent in mine pit wall profiles. A suspended measuring rope was used to measure horizon thickness. Notes and accompanying photographs were taken on horizon thickness and characteristics. In the lab samples were dried at 40°C and a mortar and pestle was used to prepare bulk samples for mercury analysis by Zeeman atomic absorption spectrometry (see 3.2.7).

### **3.2.5 Grain size**

Bedload sediment samples ranged from stream gravels with pebbles larger than 4mm, to low energy shoreline samples collected from large rivers comprised of sand and clays. In the lab bedload samples were dried at room temperature and sieved to standard ASTM size fractions using an auto seive shaker. Prior to sieving, bulk sub-fractions were extracted for independent mercury analysis.

### **3.2.6 Organic matter**

Analysis of Particulate Organic Matter (POM) in bedload sediment samples was made to investigate correlation between organics in the sediment and mercury concentration. This analysis was conducted on a subset of the bedload sediment samples. POM was estimated by loss-on-ignition (LOI). Small crucibles containing precision weighed sediment samples were heated to 440°C for five hours, let to cool, and weighed again, based on the method of Schumacher (2002).

### **3.2.7 Mercury Analysis**

Mercury measurements were made on suspended and bedload sediments using a Lumex RA-915+ Mercury Analyzer and RP-91C attachment. The instrument uses an electrode-less mercury discharge lamp with magnetic field to employ differential atomic absorption spectrometry, specifically implemented using Zeeman atomic absorption spectrometry with high frequency modulation of light polarization (Sholupov and Ganeyev 1995).

Samples were inserted into the Lumex RP-91c attachment on quartz applicator spoons, ionizing the mercury by thermal decomposition in the attachments' two section atomizer (700°C, 800°C). Standard reference materials NIST-2709 and NIST-405 were used for instrument calibration and accuracy testing. Size fractions greater than 0.125mm, including bulk samples, were crushed using an agate mortar and pestle prior to analysis. In the case of suspended sediments, the microfiber membranes containing were folded, and rolled using tweezers and carefully fit into the quartz applicator spoons.

Because the amount of dissolved mercury is small relative to total mercury transport, and collection/preservation protocols are very difficult for remote sampling campaigns, a decision was made not to analyze water samples which had been sampled and prepared (filtered and acidified) in the field.

### **3.2.8 Error in TSS and mercury analysis**

Methods used to control and assess measurement error included: (i) in situ collection of duplicate and triplicate TSS samples; (ii) each sediment sample mercury analysis was done in duplicate, and triplicate if initial results differed by more than 10% (average of 2 nearest measurements used for solution); (iii) membrane blanks were created in situ using field equipment to filter de-ionized water; (iv) testing for analytical instrument drift by analyzing standard reference material NIST 2709 between each sample run, followed by re-calibration when necessary; (v) multiple analysis of standard reference material and a field sample (12 independent measurements) to determine analytical precision; and (vi) analysis of individual size fractions, followed by comparison with bulk mercury measurements. Based on these approaches, combined TSS and mercury measurement error was determined to be not larger than 5%.

### **3.2.9 X-Ray diffraction**

X-ray Diffraction analysis was carried out on suspended sediment (membrane) samples and on bed-sediment samples. Analysis was done on samples from large rivers as well as stream and tributaries - including sites adjacent to mining operations.

Sieved bed-sediment fractions were analyzed for sediments from three separate locations to investigate the relationship between grain size and mineral transport. Bedload sediments were ground in an alumina mortar before analysis.

Polycarbonate membranes containing suspended sediments were attached to glass slides with double-sided tape. Membranes with coarse material were scraped of their sediment so it could be ground in an alumina mortar, and smeared onto a zero-diffraction quartz plate with ethanol.

Step-scan X-ray powder-diffraction data for all the samples were collected over the range  $3-80^{\circ}2\theta$  with  $\text{CoK}\alpha$  radiation on a standard Siemens D5000 Bragg-Brentano diffractometer equipped with a Fe monochromator foil, 0.6 mm ( $0.3^{\circ}$ ) divergence slit, incident- and diffracted-beam Soller slits and a Vantec-1 strip detector. The long fine-focus Co X-ray tube was operated at 35 kV and 40 mA, using a take-off angle of  $6^{\circ}$ .

Mineral identification was done using the International Centre for Diffraction Database PDF-4 and Search-Match software by Siemens. XRD analysis was conducted at the Electron Microbeam and X-ray Diffraction Facility at the University of British Columbia under the supervision of Mati Raudsepp.

#### **3.2.10 Gold analysis by fire assay**

Fire assay analysis for gold determination was done by fusion and lead cupellation. Fusion was done at  $1065^{\circ}\text{C}$  in a dry flux, precipitating precious metals from the ore sample into a lead button. Inductively Coupled Plasma Emission Spectroscopy (ICP-ES) was used to determine silver and gold content. For samples possessing  $>10\text{ppm}$  gold, nitric acid was used to remove silver followed by lead cupellation with gravimetric finish using analytical balance to determine gold content. These gold assay procedures were performed by ACME laboratory in Vancouver BC.

### **3.3 Results and discussion**

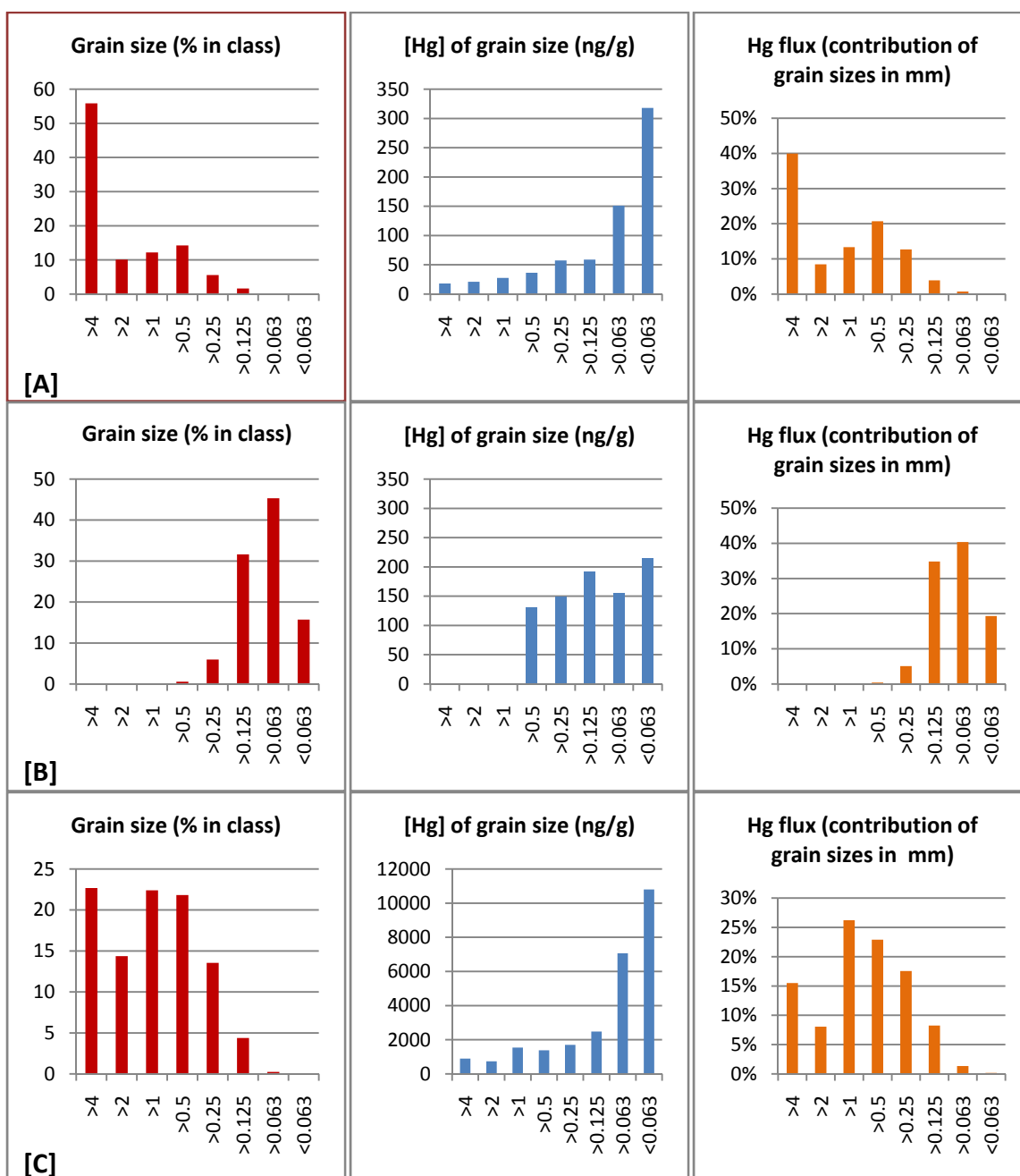
#### **3.3.1 Mercury concentration of native sediments**

Soil and sediment samples collected at multiple pits and analyzed for mercury, revealed considerable variation based on sediment properties. Sediments collected from pit walls in the Galangan region averaged 270ng/g (ppb)  $\pm 20\%$  (n=19). Quartz rich sediments collected from mine pits in the Sampit river basin had 36 ng/g  $\pm 20\%$  (n=3), while pit sediments collected from mine pits in an upland catchment in the Hamputung river basin (upper Kahayan River) with ferrisollic soils, was 197  $\pm 35\%$  (n=3). The native sediment mercury levels detected at Galangan (in the Katingan River basin), and in the upper Kahayan River basin are high relative to mean values reported in tropical soils by other authors, but within the upper range of values reported elsewhere (Grimaldi et al., 2008; Roulet et al., 1998).

#### **3.3.2 Bedload sediments**

Mean mercury concentration of river bedload sediments was 525ng/g (ppb), with a median of 134ng/g (bulk samples; n=26). Excluding five concentrated samples from one mining area, however, the mean value was 152.8ng/g, with a median of 62ng/g. Analysis of the data with consideration of ASGM influence, implies that background mercury concentrations of bulk riverbed sediments range between 25 and 125ng/g (ppb).

Particle size has a major influence on mercury carriage and thus transport, such that bedload mercury flux apportions similarly to bedload grain-size distribution.



**Figure 10. Grain size analysis and mercury concentration of three representative bedloads (x-axis represents size fractions, in millimeters). [A] Kahayan River at Rungan River convergence (bulk sediment Hg 187ng/g); [B] Kahayan River at Tambung Miri (bulk sediment Hg 25ng/g); [C] Barito River at Tambung Kunyi (bulk sediment Hg 1475ng/g). Note that mercury flux follows grain-size distribution.**

Main-channel sediment mercury concentrations ranged from 46ng/g to 504ng/g, with a mean of 235ng/g and a median of 241ng/g. Barito and Kapuas channel samples had the highest mercury levels, followed by the Katingan, Kahayan and Seruyan rivers. Stream and tributary sediment samples were more variable than main channel samples, with min and max values ranging widely from 9ng/g to 4,500ng/g.

Elevated mercury levels were detected in each of the 5 samples collected around the vicinity of Mount Muro, on the upper Barito River. Two of these samples, collected from the main channel, averaged 1,700ng/g. The other three, collected from streams in the vicinity, averaged 2,400ng/g. These values represent enrichment in mercury concentration by an average factor of twenty, and mercury was equally concentrated across size fractions (same pattern of increase in concentration towards fines as noted in less concentrated samples). Contaminated sediments were not confined to drainage of tailings effluent. Sediment from a stream without mining operations had bulk sediment mercury concentration of 1,900ng/g, providing evidence for localized deposition of mercury volatilized from ASGM nearby.

Highest bulk sediment measurement was sampled from a stream which passes through the mining community of Mangkuhoi (village 15km to the south-east of Puruk Cahu). The watershed drains an area of 135km around the community, and was sampled at its mouth where it enters the Barito River. Approximately 3km upstream from this location, effluent from whole-ore amalgamation circuits (described in Chapter 2; see Photo panels 45-47), and from nearby cyanidation operations (see Photo panels 52, 53), drain into the stream. Bulk sediment mercury content was 4,500ng/g. Stream water alkalinity was extremely high at this location (1.2eq/L) resulting from additions of lime or soda ash in the mineral processing with CIP cyanidation. Dead minnows were observed floating in this stream.

Stream and riverbed sediment samples in the vicinity of Mount Muro average 2,100ng/g mercury. In this case, it is clear that these elevated mercury levels (20 times background

on average) are due to mercury released by ASGM activities. Ecological health guidelines do not exist for stream sediment (the CADEPA safety guideline for soil is 10,000ng/g).

Mercury analysis of individual bedload sediment size fractions revealed a strong inverse correlation between mercury concentration and particle size, with silt and clay fractions responsible for highest mercury concentrations. This does not, however, imply that the finest bedload size fractions are responsible for the lion's share of bedload mercury transport. Instead, mercury flux is controlled principally by apportionment of grain size, as represented in Figure 10. Mercury present in highly enriched samples was distributed in the same manner as lower mercury samples, with finest fractions having higher mercury levels than larger sediment particles.

### **3.3.3 Suspended sediments**

TSS and associated particulate mercury flux were less variable in main river channels than in tributary rivers and streams, which are affected to a greater degree by local phenomena due to their smaller size. TSS of major river channels varied from 26.7mg/L in a calm reach near the mouth of the Barito River, to 278.2mg/L in a fast flowing reach of the Kahayan River. TSS mercury concentration, ranged from 240ng/g to 1600ng/g. The product of these two analyses is particulate mercury per litre of water, referred to in this chapter as particulate mercury flux. For large river samples, particulate mercury flux ranged between 27.9ng/L and 254.2ng/L. A storm surge sampled during a turbulent flow on the Kahayan River had 639.8mg/L suspended sediment and has been treated as an outlier; this sample is discussed in section 3.3.5.

TSS of tributaries and streams varied from 1mg/L in a pristine stream in headwaters of the Kahayan basin to 1294.8mg/L, immediately downstream of mining activities in the Sampit river basin. TSS mercury concentration associated with these samples ranged from 150ng/g (ppb) to 10,900ng/g, resulting in TSS mercury flux ranging from 10 to 1,114ng/L (ppt).

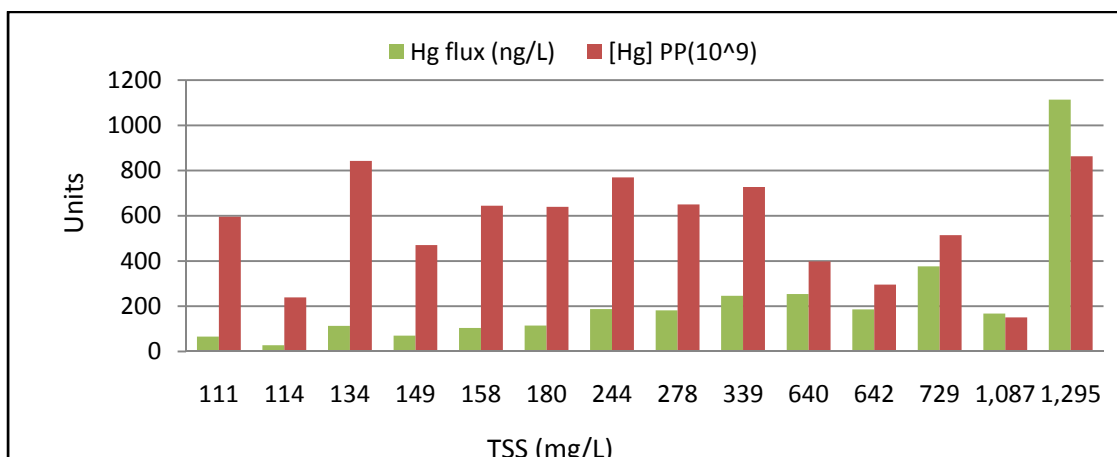
Table 2 provides a statistical overview of TSS measurements made on main river channels, and on streams and tributaries. In comparison to TSS mercury flux, dissolved mercury flux in tropical river waters range from 0.5 to 10ng/L (Telmer et al., 2006), illustrating that dissolved transport is a minor contributor to riverine mercury flux.

	River Samples			Stream Samples		
	TSS mg/L	Hg (ng/g)	Hg (ng/L)	TSS mg/L	Hg (ng/g)	Hg (ng/L)
Median	53.7	905.5	55.7	157.0	748.8	121.2
Mean	86.8	1004.8	68.1	351.0	1760.4	207.2
RSD%	80.7	45.6	57.0	120.4	158.5	134.0

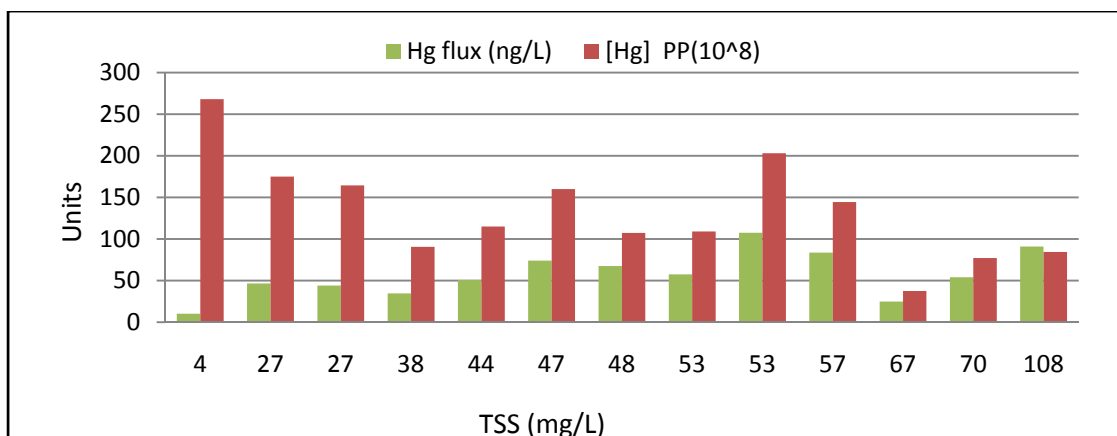
**Table 2. Suspended sediment statistics of large river samples, from 14 sampling events on six 6 first order channels, and from 15 sample events on streams and tributaries sampled across five of the large river basins.**

High TSS waters result in greater mercury flux, relative to low TSS waters. However, the inverse correlation between TSS and mercury concentration means that fine particulates, on average, have considerably higher mercury concentrations than larger particulates. As a result, in many of the samples with low concentrations of fine sediment in suspension, particulate mercury flux remained near mean levels. In contrast, high TSS samples with larger average particle size have lower average mercury concentration, but in these samples mercury flux increases due to elevation in the total mass of sediment, including fines.

Mercury analysis of the TSS sample set (n=30) is presented using four figures, below. The dataset is divided into two groups: high TSS samples (1295-111mg/L), and low TSS samples (108-4mg/L).



**Figure 11. Mercury concentration and flux associated with High TSS water samples. Each set of bars represents one TSS sample. [Hg] PP(10<sup>9</sup>) = parts per billion.**



**Figure 12. Mercury concentration and flux associated with Low TSS water samples. Each set of bars represents one TSS sample. [Hg] PP(10<sup>8</sup>) = parts per hundred million.**

At TSS levels over 100mg/L mercury flux rises sharply with increasing TSS, and TSS Hg concentration is only slightly higher, on average, at lower TSS levels – see figure 13. At TSS levels below 100mg/L mercury flux rises, but not dramatically, with increasing TSS. This is because in low TSS samples with very fine particulates, a considerable amount of mercury remains in flux (TSS Hg concentration is much higher at very low TSS concentrations) – see Figure 14.

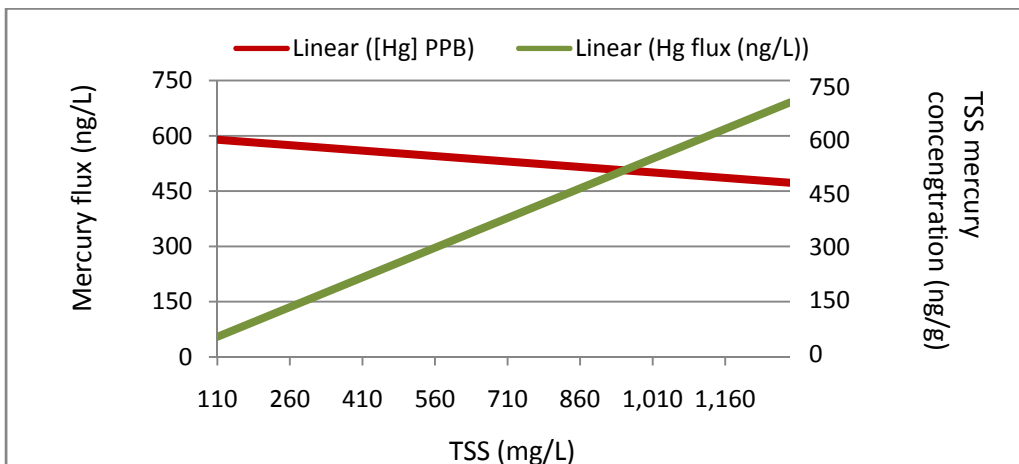


Figure 13. TSS mercury data (sample trends) for high TSS water samples.

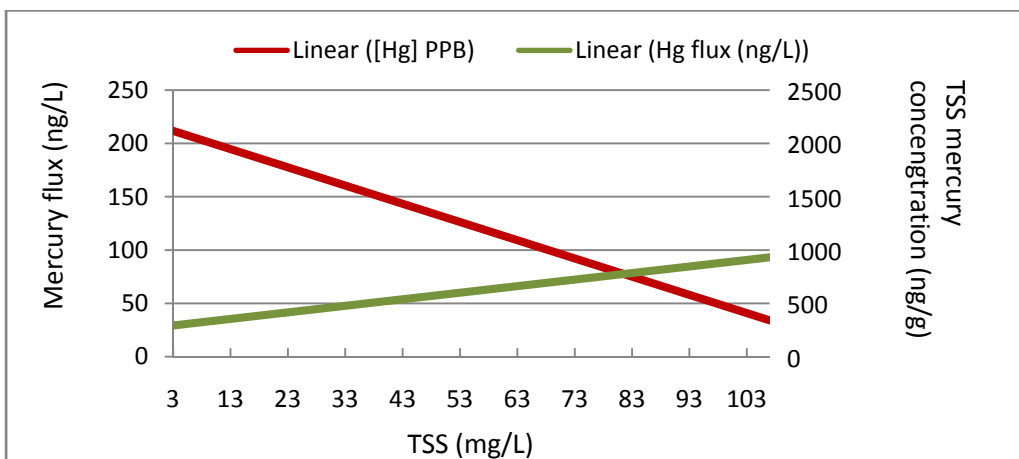


Figure 14. TSS mercury data (sample trends) for average TSS water samples.

Mercury flux is less variable than TSS concentration or mercury concentration in the suspended load. This is a manifestation of the inverse relationship between the latter - see Table 3.

River	Location	TSS mg/L	[Hg] (ng/g)	Hg flux (ng/L)
Barito	Bangarmasin	26.7	1645	44.1
Barito	Tambung Kunyi	44.2	1150	50.8
Barito	Dockside	26.6	1750	46.6
RSD %		31	21	7
Kahungoi	300m downstream of active mining	338.7	727.5	246.3
Kahungoi	downstream of inactive mining_A	134.3	843.0	113.2
Kahungoi	downstream of inactive mining_B	11.7	10,900	127.5
RSD %		102	140	45

**Table 3 Within-river variability of TSS, mercury concentration, and mercury flux for three different locations sampled on both the Barito River, and on the Kahungoi tributary of the Kahayan River.**

It is important to put these mercury concentrations figures in perspective. The Indonesian standard for safe drinking water is 1000ng/L (Public Health Minister of Indonesia, 2002). All but one of the water samples waters in this campaign meet this criterion, including several water samples with TSS above 500mg/L.

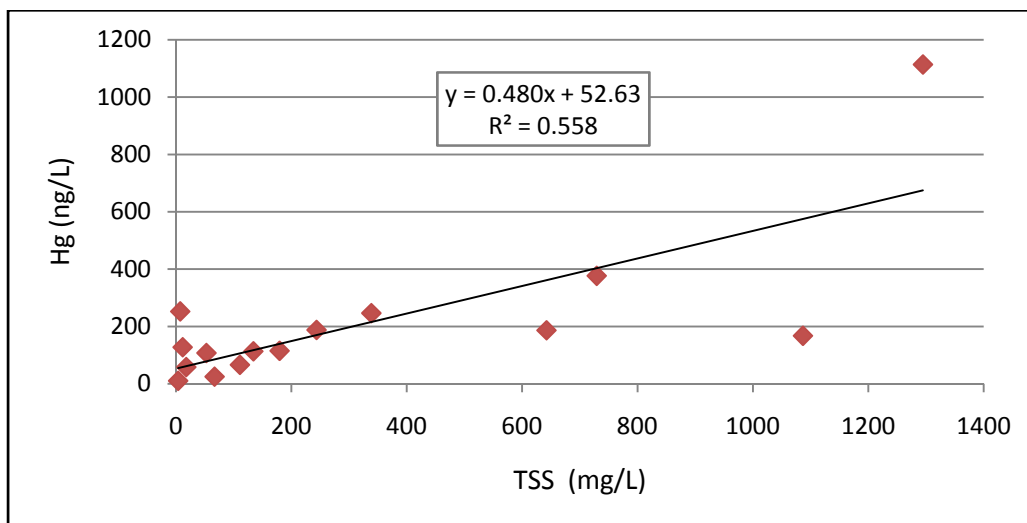
### 3.3.4 Suspended sediments near mining activities

Sixteen suspended sediment samples collected at eleven different streams and tributaries locations (from five of the main river basins) were taken to investigate the effects of mining on sediment and mercury transport. In catchments of the Kahayan, Katingan and Sampit rivers, stream samples were collected from above and below mining operations to directly quantify impacts of mining.

Waters within 500m downstream of active mine dredging had 100 times the suspended sediment as undisturbed waters, on average. In clear water streams with mining, sediment loads were increased up to 1500 times. In one such stream – the Hamputung River, only a few active mining operations (<10) caused a dramatic increase in TSS from less than 10mg/L in the rivers head waters, to more than 500mg/L where it meets with the Kahayan River, 30km downstream from the uppermost mining operation. Mercury

flux associated with elevated sediment transport increased below mining (within 500m) by a factor of four in the sample set, on average.

Stream water TSS near and within 50km downstream of mining areas correlates with mercury flux (R squared value of 56%, see Figure 15).



**Figure 15. Correlation between stream TSS and mercury flux near mining activities.**

More than five kilometres distant from mining operations (but less than 50km distant), suspended sediments were considerably reduced compared to immediately below mine sites, but remained elevated relative to above mining operations by a factor of approximately 20. This suggests that during normal flows, a large proportion of mobilized sediments re-settle in the stream bed near mining operations.

River Basin	Stream Name	Site key	TSS	Hg (ng/g)	Hg (ng/L)
Barito	Mangkuhoi Stream	4	17.9	3260	58.3
Kapuas	Peat River	4	3.8	2680	10.2
Kahayan	Miri	3	67.0	375	24.8
Kahayan	Sonong	2	52.9	2030	107.5
Kahayan	Sonong	1	1086.8	151	167.4
Kahayan	Kahungoi	1	338.7	728	246.3
Kahayan	Kahungoi	4	11.7	10900	127.5
Kahayan	Kahungoi	2	134.3	843	113.2
Kahayan	Hamputung	1	729.3	515	376.5
Kahayan	Hamputung	1	642.3	296	186.4
Katingan	Kalanamaan	3	179.7	640	114.9
Katingan	Hampilat	3	243.7	770	187.6
Sampit	Handu	3	110.9	596	66.1
Sampit	Hangar Stream	1	1294.8	863	1113.8

Site Key	Legend	mean	mean	mean
1	<5km downstream of mining (5)	818	510	418
2	<5km downstream of not operating mining (2)	94	1437	110
3	5 to 50 km downstream of mining (4)	150	595	98
4	not directly affected by mining sediments (5)	8	12735	112

**Table 4. TSS and Mercury measurements from streams and tributaries affected by mining. The sample site key explains site proximity to mining activities, is provided in the lower part of the table.**

Suspended-sediment measurements around mining activities in the Hamputung River basin, and on the Barito River near Tambung Kunyi reveal that the composition of sediments being mined is the dominant control of siltation. Significantly less sediment remains in suspension when miners exploit loose river bed gravels, as compared to areas where overbank sediments and other fine-grained and clay-rich ore bodies are mined. In both cases, however, very fine particulates are brought into suspension. Finest fractions may constitute only a miniscule proportion of the total sediments mobilized, but remain in suspension for long distances and provide abundant adsorption sites for mercury.

Whether or not mining causes increases in TSS of a different fineness than storms was considered but because mobilized sediment compositions vary widely between operations, a consistent generalization cannot be made. It is postulated that storm

runoff is likely to have greater proportions of organic matter from overland flow, which would increase carrying potential for mercury.

It is clear that mining increases the mass of sediment available to be transported, and that storms mobilize sediment available for transport. This applies to sediments deposited downstream of mining operations but also tailings deposited or re-settled near to mine sites, because natural barriers to erosion have been removed by mining.

### **3.3.5 Suspended sediments in main river channels**

The Barito, Kapuas and Kahayan rivers (main channel) were each sampled in upper catchment locations as well as mid-to-lower catchment locations, distant by 350km, 185km and 130km respectively. The Katingan, Sampit and Seruyan rivers were only sampled in mid-to-lowland catchment locations. In rivers sampled near their mouths (Barito and Kapuas) TSS concentration was lower relative to upstream concentrations because flow velocity has decreased, causing sediments to settle out of suspension.

TSS sampled on six occasions at four locations along the Kahayan River ranged from 46.6mg/L to 278.2mg/L with an outlier of 639.8mg/L during a storm flow - demonstrating dynamic sediment flux conditions. Excluding the storm flow, measured TSS was highest in the Kahayan, Kapuas and Katingan rivers (158, 128, and 70 mg/L means, respectively) followed by the Seruyan, Sampit and Barito rivers (52.7, 38.2, and 32.5 mg/L means, respectively) - see Figure 16. Due to a larger number of samples, error bars produced for the Kahayan River are likely to be most representative of within river variability for each of the parameters in Figure 16, although this river is heavily affected by mining activities which is thought to increase variability. For large river samples, correlation between TSS and mercury has an R squared value of 72% - see Figure 17.

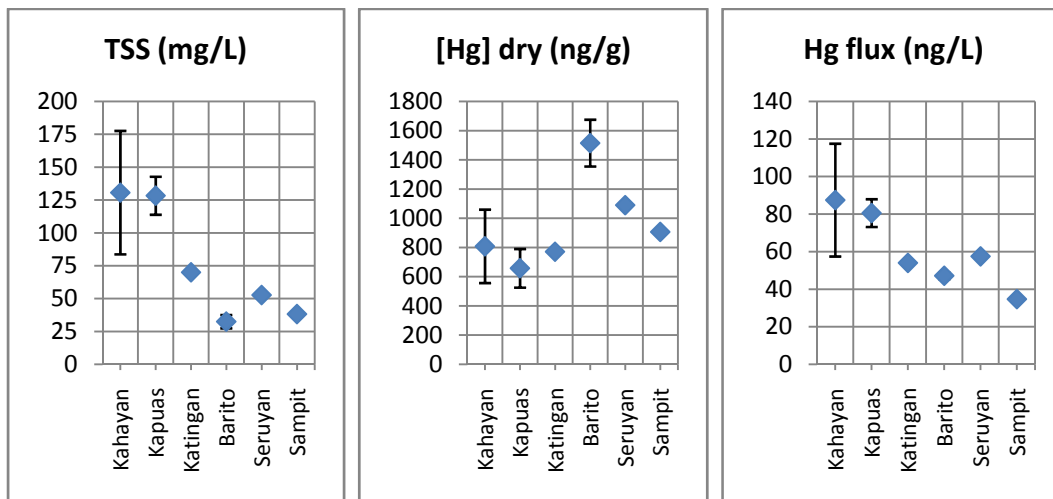


Figure 16. Main Channel TSS Statistics, excluding storm surge outlier on the Kahayan River. Rivers with no error bars had limited sample instances.

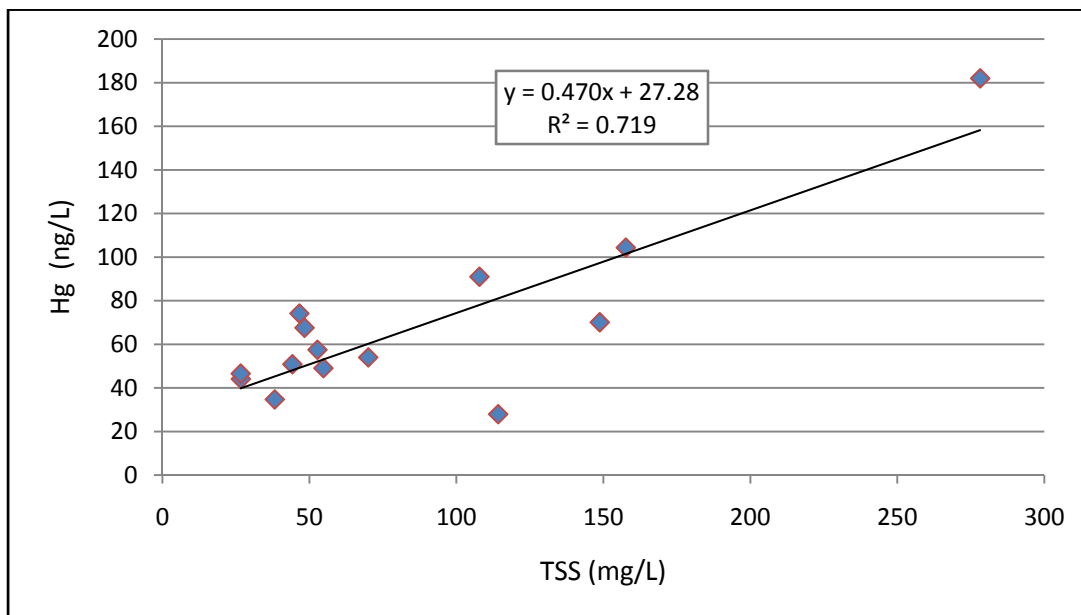


Figure 17. Correlation between TSS and mercury flux from main river channel samples.

On the Kahayan River, three depth profiles were collected from surface, 1.5m, and 3m depth. Analysis of these samples did not provide evidence that TSS or mercury flux varies significantly between these depths and is therefore not presented or discussed further.

### **3.3.6 Suspended sediments during high water flows (storm surges)**

Rapid rises in river flow following sustained monsoonal rains are common in Central Kalimantan. One such flow was sampled on the Kahayan River on July 5<sup>th</sup>, 2008 after approximately 48 hours of nearly continuous intense rainfall. This sample was collected at Tambung Miri approximately 300km from the river mouth. Basin area above the sample site is approximately 2000km<sup>2</sup>. The village of Tambung Miri sits atop a 30 meter high levee in a series of 1 kilometre wide river meanders. River level rose four meters in a span of 48 hours and turbulence increased dramatically. A surface water sample was collected from a floating dock 6 meters from the steep shoreline.

Turbulent flow caused sand grains to be suspended in the surface water sampled. Grain counts indicated sand particles 0.5-1.0mm were responsible for approximately 15% mass in suspension with 30, 30, 15 and 10% represented by smaller fractions (0.25-0.5, 0.125-0.25, 0.0625-0.125, and <0.0625mm, respectively). This was the only sampled instance with coarse sediment grains larger than 0.125mm in suspension.

TSS was 640mg/L, six times higher than measured at the same location a week earlier. Relative to two previous sampling instances at the same location the storm flow increased mercury flux by a factor of nine (254ng/L, from 28ng/L). This effect is contradictory to other instances of high TSS resulting in only small increases of mercury flux. This data point appears to provide evidence for overland flow - caused by the storm, causing mercury flux to spike. This has been reported by numerous studies (Grigal 2002).

A day later the same surge in flow was sampled fifty kilometres downstream (at Kuala Kurun) from a less turbulent more laminar river reach. Lower TSS (158mg/L) but higher

TSS mercury concentration (645ng/g) resulted in measured TSS mercury flux of 104ng/L. This site was sampled again two weeks later, during another strong flow (high flow but still laminar). Measured TSS was 47mg/L, considerably lower than previous TSS measurements at the same location (mean of 106mg/L). Despite high water flow, this measurement was the lowest TSS of all six sampled instances on the Kahayan River. Because this sample instance was made during the declining period of the hydrograph, it is postulated that the preceding storm flows evacuated sediments available for transport. Mercury concentration of this TSS sample was elevated (1600ng/g) relative to other measurements (mean of 775ng/g) such that mercury flux per unit water was not changed significantly from mean levels (75ng/L, from mean of 94ng/L). These measurements illustrate that the fine sediment fraction is most concentrated in mercury and that variations in abundance and source of these fine particulates can cause mercury flux to deviate from correlation with TSS. These deviations result from dynamic processes involving fine carrier phases for mercury, and mercury mobilization associated with high water flows.

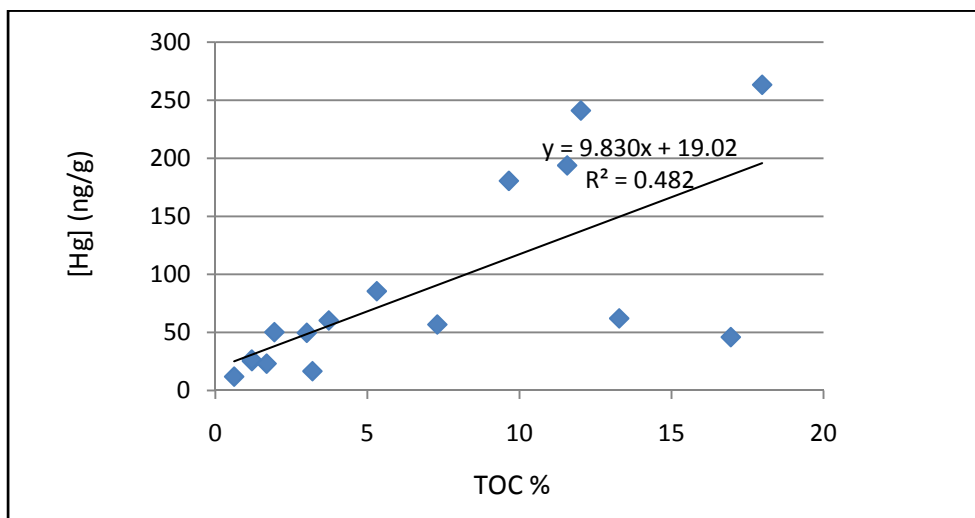
### **3.3.7 Variability of mercury in sediments**

Differences in mercury concentration between fine (sieved) fractions of sampled bedload, and TSS mercury concentration, illustrate that mercury associated with fine particulates in both components vary in space and time. At most sites mercury concentration of TSS was considerably higher but at other sites, bedload fine fractions had twice the concentration of TSS. These differences complicate source apportionment to some degree, and illustrate that mercury partitioning in river sediments fluctuates in space and time.

### **3.3.8 Organic sediments**

Two analytical approaches were used to investigate the relationship between organics in bedload sediments and mercury concentration, and both showed mercury concentrations correlate positively with organic content in sediments. LOI analysis was conducted on bedload samples. Forty-eight percent of the variance in mercury

concentrations can be explained by proportions of organic matter, in samples with less than 400ng/g mercury (n=16), see Figure 20. This relationship breaks down when highly concentrated sediment samples are included in the analysis (n=24).



**Figure 18. Total Organic Carbon in sediments (%TOC) versus mercury content (Hg ng/g) - for bedload sediment samples with mercury content below 400ng/g (ppb).**

A second approach to study the role of organics was made by independently analyzing organic sub-fractions of sieved bedload sediments. After sieving, a few of the sample fractions were left with organic detritus sorted from the sediments. For three separate bedload sample locations, this dark coloured fibrous detritus was extracted from 0.125-0.25, and 0.25-0.5mm fractions. Analyzed separately from mineral fractions, these organic sub-fractions had mercury concentrations ten times higher, on average. This result indicates the important role that particulate organic matter plays in mercury adsorption and transport. No specific analysis was made to determine the contribution of POC on suspended sediment membranes.

### 3.3.9 XRD Results

Eleven of the thirteen minerals detected by XRD in the suspended sediments were also identified in bedload sediments. Mineralogy of both suspended and bedload sediments are relatively uniform between the river basins sampled, with the exception of a few streams. Quartz occurs ubiquitously. Feldspar minerals include plagioclase, K-feldspar,

albite, actinolite and microcline - the occurrence of these minerals are pronounced in areas affected by mining activities. In terms of clay minerals, kaolinite and gibbsite are dominant, with kaolinite occurring more frequently in suspension and gibbsite more frequently in bedload. Clinocllore – a chlorite series end-member, was also common, and muscovite and biotite were prevalent as well. Less common minerals occurring in suspension include talc, the oxides goethite and anatase, and calcite. In bedload sediments less common occurrences of goethite and pyrite were identified as were occurrences of andalusite, montmorillonite, ankerite, corundum, anatase, ferrihydrite and gypsum.

Comparison of XRD results between each of the three smallest bedload size fractions from the Barito and the Kahayan Rivers reveal that there is little difference between size fractions in terms of mineralogy. Several authors have documented the importance of clays and oxides as transport carriers for mercury in river systems (Gabriel and Williamson 2004), (Slowey, Rytuba et al. 2005). The results point to kaolinite and gibbsite as dominant mercury carriers, based on their ubiquity. However it is plausible that the other clays present - including clinocllore, muscovite and biotite, and the oxides goethite and anatase, are also implicated in the adsorption and downstream transport of mercury. Particulate organic matter is suspected to play a major transport role, but mercury analyses differentiating POM from TSS was not made during this thesis.

### **3.4 Modeling sediment and mercury flux**

#### **3.4.1 Introduction**

First approximation of sediment and mercury fluxes was made using measured TSS and mercury concentrations and 1<sup>st</sup> order estimates of water flux. To improve and broaden these flux estimates, an expert system approach has been used to model fluxes in each of the six large river channels sampled. These flux estimates incorporate regional hydrographic information to improve annual flux budgets for sediment and mercury, and have been scaled to entire basin areas.

The total land area contributing discharge to the sampled river sites is vast. Basin area upstream of sampled river sites is 115,000km<sup>2</sup>, representing 76% of the provinces total area of 152,000km<sup>2</sup>. Scaling the model to incorporate entire basins increased the area to 141,000km<sup>2</sup> (93% of the provincial landmass; an area approximately five times the size of Vancouver Island).

### **3.4.2 Methods**

Primary parameters required for modelling sediment flux are suspended sediment concentration, and river discharge. However, discharge data do not exist for the sampled rivers and data from only three rain gauges are available from the province. Given this paucity of data, a hydrological model was constructed using (i) precipitation data from the Tropical Rainforest Measurement Mission (TRMM) dataset, cross-checked with the available rain gauge measurements; and (ii) a discharge hydrograph from a nearby river in East Kalimantan – a proxy river used to establish the regional relationship between precipitation and runoff.

The Tropical Rainforest Measurement Mission (TRMM) – a collaboration between American and Japanese space agencies, uses a passive microwave sensor aboard a satellite platform to measure microwave energy emitted by the Earth and its atmosphere in order to quantify water vapour, cloud water, and rainfall intensity in the atmosphere. Precipitation data is available for the entire tropical region at daily temporal resolution and quarter degree (27.8km) resolution. Data quality has improved significantly since the mission was launched thanks to calibration with ground stations (Adler, Braun et al. 2007).

To utilize this dataset, two-dimensional maps of precipitation contours averaged over fifteen day time periods were derived using the TRMM Online Visualization and Analysis System. Watershed boundaries were derived using calibrated Shuttle Radar Topography Mission (STRM3) digital elevation data (NASA). By superimposing watershed boundaries over precipitation plots, total rainfall was estimated within watershed boundaries at 15 day time scales using a polygon measurement tool in ArcGIS<sup>TM</sup>.

Additionally, a six month discharge dataset was measured at the mouth of the Berau River in East Kalimantan between June and November of 2007, and was kindly provided for use in this thesis by Dr. Frans Buschman. Discharge was measured at the mouth of the Berau River by Buschman's team of Dutch scientists, from June to November of 2007. Horizontal Acoustic Doppler Current was used to measure flow at ten minute intervals throughout this period and the dataset was adjusted for tidal currents (Hoitink, Buschman et al. 2009).

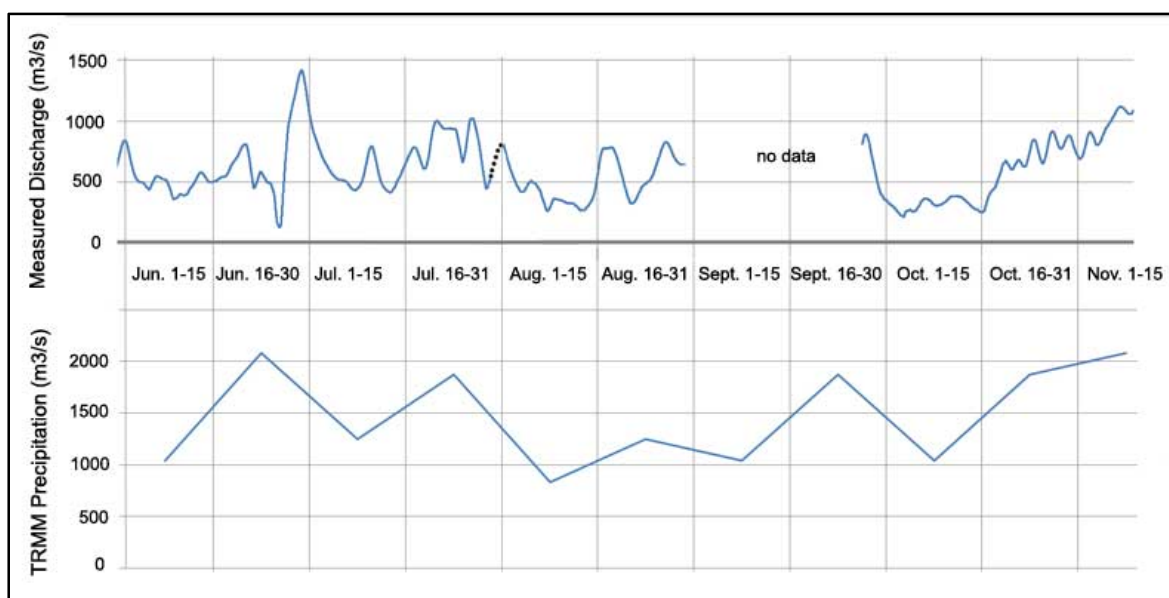
The Berau basin is 18,000 km<sup>2</sup>, making it similar in size to each of the Kapuas, Katingan and Sampit River basins of Central Kalimantan. Its northern headwater boundary is situated two hundred kilometres northeast of the Barito's, but the basin drains eastward through East Kalimantan towards and into the Makassar Strait, instead of Southward to the Sea of Java. Similar to the basins studied in Central Kalimantan, the Berau basin is covered by lowland and highland tropical rainforests. It is dominated by similar geological assemblages, and is void of significant lakes which would buffer large hydrologic events. These features make the Berau River an ideal proxy for the large rivers of Central Kalimantan.

### **3.4.3 Runoff Coefficient**

Runoff coefficients for the Berau River basin were determined by comparing TRMM precipitation data with river discharge. Run-off coefficients for each fifteen day period were derived from the quotient of precipitation and discharge (see Figure 21). Runoff coefficients fell between 30% and 50% of precipitation on 15 day intervals, and overall had a mean of 42%. This implies that on average, 58% of rainfall is evapotranspired, which agrees well with Bonell and Bruijnzeel (2004). This value (42%) was subsequently used as the proxy runoff coefficient.

Extreme highs and lows in the Berau hydrograph underscore intense hydrologic pumping of Borneo's landscape. A large storm in later June increased discharge from 200 to more than 1,400m<sup>3</sup>/s within one week, after which it dropped to around 400m<sup>3</sup>/s within the following week. Min, mean and max discharges from the dataset are 0.010,

0.033 and 0.078 m<sup>3</sup>/s/km<sup>2</sup>. This six month variation is roughly equal to twenty year normalized min, mean and max values recorded at one of the most variable discharge stations in the Amazon – the Jiparana River at Jiparana, although this station represents discharge from roughly twice the area (Marengo 2005), (Costa, Oliveira et al. 2002).



**Figure 19. Hydrographic discharge measurements made on the Berau River in 2007 by Buschman et al.(2008); and coincident precipitation hydrograph modelled in GIS using TRMM precipitation data plots, watershed boundary, and 42% runoff coefficient.**

#### 3.4.4 River discharge estimates

Precipitation rates for each of the large river basins in the study area were determined using fifteen day TRMM plots for all of 2008, and watershed boundaries. From these precipitation estimates, coarse resolution hydrographs were derived using the 42% runoff coefficient.

Additionally, to investigate the magnitude of 2008's highest flows (including the storm event sampled), five day TRMM plots were analyzed over peak precipitation events during March 16-31 and November 1-15 of 2008. Shortening of the averaged TRMM precipitation period to five days increased averaged basin precipitation rates up to 22mm per day, from a maximum of 18mm per day when 15 day plots were used. The five day max precipitation periods were subsequently used to derive maximum

discharge rates for each basin. The same runoff coefficient (42%) was applied to these high discharge events (based on five day intervals), despite the possibility that heavy precipitation would likely cause runoff coefficients to rise temporarily.

### 3.4.5 Suspended Sediment Transport

First approximation mass balances for annual sediment and mercury fluxes moving past the sampled locations were calculated from measured TSS and associated mercury values, and a first order discharge estimate (see Table 5).

River	Basin area (km <sup>2</sup> )	Discharge (m <sup>3</sup> /s)	TSS (mg/L)	Hg (ng/L)	Sediment flux		Mercury flux	
					(t/d)	(t/a)	(kg/d)	(kg/a)
Barito	61,582	2332	32	47.1	6,458	2,357,262	9.5	3,468
Kapuas	13,594	545	128	80.5	5,959	2,175,038	3.8	1,385
Kahayan	6,958	306	131	133.9	3,406	1,243,255	3.5	1,291
Katingan	12,701	556	70	54.0	3,315	1,209,846	2.6	946
Sampit	12,360	541	38	34.7	1,760	642,224	1.6	592
Seruyan	7,554	312	53	57.5	1,402	511,827	1.5	566
Totals	114,749				22,300	8,139,453	22.6	8,247

**Table 5. Mass Balance for TSS and mercury, based on average conditions and ignoring extreme events.**

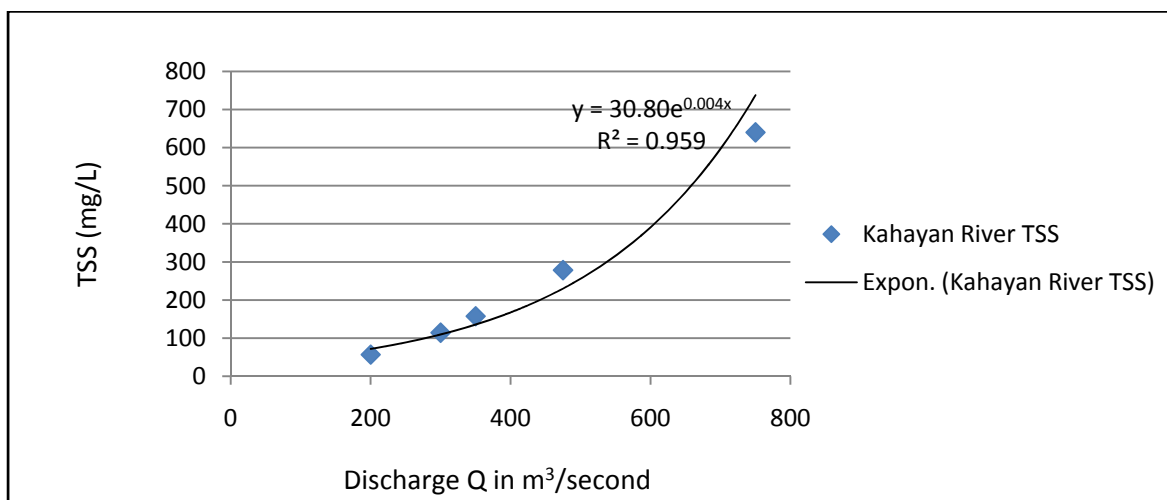
According to this mass balance, approximately twenty-two thousand tonnes of sediment (8,150 cubic meters) and 22.6kg of mercury were collectively transported via suspended sediments past the sampled sites on the day sampled. Extrapolating this mass balance across 2008 would underestimate flux budgets because high discharge flows would not be represented, nor would bedload sediment transport.

### 3.4.6 Sediment Rating Curve

In the absence of regular suspended sediment concentration measurements, sediment rating curves can be used to estimate or predict suspended sediment fluxes. Sediment rating curves of large rivers have logarithmic shapes with lower sediment loads during weak flows and concentrations increasing logarithmically with flow energy. Even from limited datasets, generalized sediment rating curves can be developed and applied for

the purpose of predicting or estimating sediment fluxes (Asselman 1999) (Hansen and Bray 1993) (Horowitz 2003).

Kahayan River TSS samples collected on six occasions at four different locations exhibited positive correlation between discharge and suspended sediment. On this basis a sediment rating curve was created for the Kahayan River, based on the range of measurements made. To develop the rating curve TSS values were matched with adjusted discharge intervals to produce a rating curve representative of the measurements made. This approach is advocated by (Hansen and Bray 1993) as well as (Jansson 1996), in order to produce rating curves from limited sampling campaigns. An exponential regression line was fit to the data to produce the rating curve (Figure 20).

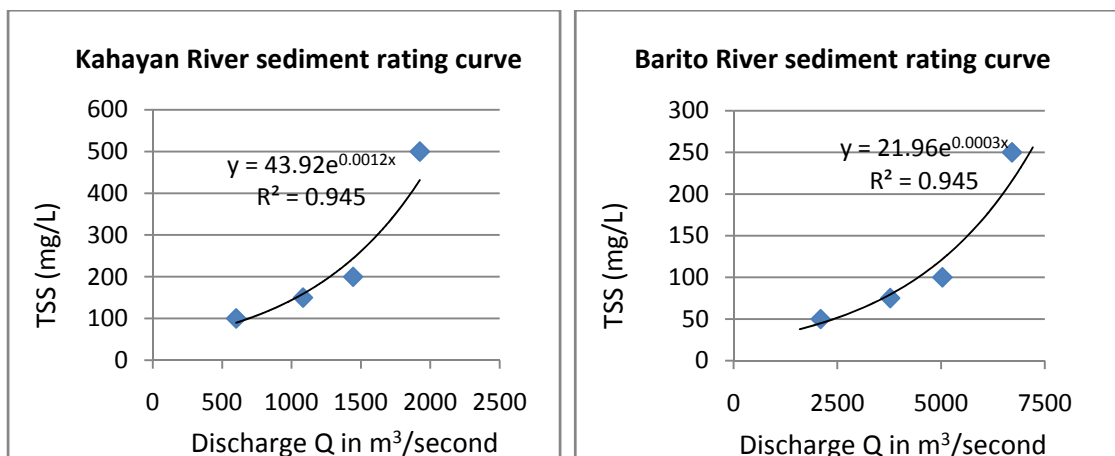


**Figure 20. Sediment Rating Curve for the Kahayan River (Discharge in m<sup>3</sup>/s on the X axis versus TSS in mg/L on the Y axis).**

Assessing the uncertainty of the Kahayan River rating curve is not possible without a larger set of measurements. Uncertainty of instantaneous sediment transport predictions based on rating curves are typically one half to twice the value of instantaneous measurements for large rivers, but this uncertainty decreases dramatically as the prediction period grows (Horowitz 2003). For this reason, rating curves can be very effective for deriving annual flux estimates.

The Kahayan River rating curve was used as a basis for creating proportional rating curves for the adjacent rivers sampled. Measured TSS concentrations on the Kahayan, Kapuas and Katingan Rivers (mean of 110mg/L  $\pm$ 31%) were roughly twice the average concentration measured on the Barito, Sampit and Seruyan rivers (mean 41mg/L,  $\pm$ 25%). The associated TSS mercury data also fit this classification scheme, with mean TSS mercury concentrations of 745ng/g  $\pm$ 11%, and 1171ng/g  $\pm$ 27%, respectively, resulting in mercury flux concentrations of 46ng/L  $\pm$  24% and 74ng/L  $\pm$  25%. Based on this classification scheme, two generalized rating curves were developed, one for each river class.

Suspended sediment concentrations of 100, 150, 200 and 500mg/L; and 50, 75, 100 and 250mg/L were used to create rating scales for the two river classes. Suspended sediment concentrations were paired with discharge intervals for each river, scaled so that peak sediment concentrations (500 or 250mg/L) were matched with maximum discharge flow intervals (Figure 21).



**Figure 21. Generalized sediment rating curves, based on the Kahayan River curve; Discharge in m<sup>3</sup>/s on the X axis versus TSS in mg/L on the Y axis.**

### 3.4.7 Flow Duration

Flow duration curves indicate the percent time that specified discharge intervals are exceeded, and thus can be used to estimate sediment flux by associating sediment

concentration with flow intervals. The annual hydrograph is required to produce an annual flux estimate.

A flow duration curve was developed for the six month Berau River discharge dataset, and used to model each of the large rivers in Central Kalimantan. Discharge ranges were classified into fourteen equal intervals, which were used to create flow duration curves proportional to the Berau River curve (Figure 22). Sediment ratings were then applied to each flow duration interval (Table 6).

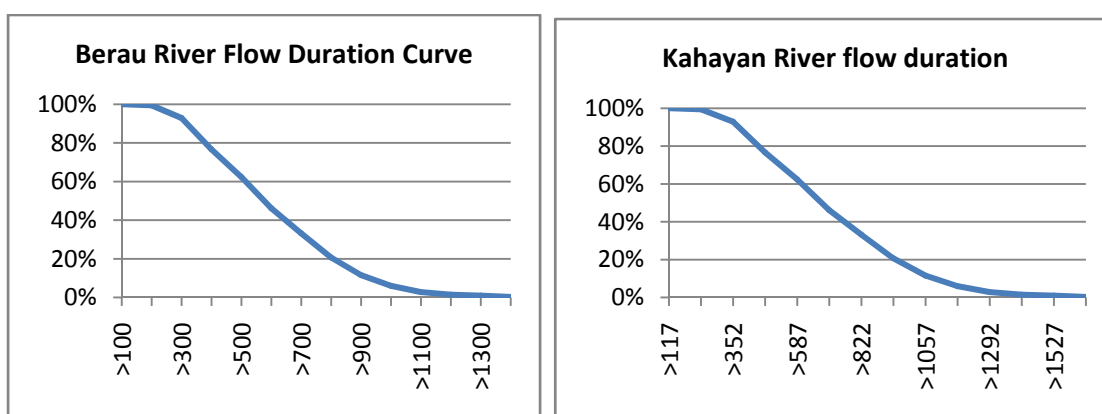


Figure 22. Flow Duration curves for the Berau River, and the Kahayan River.

Discharge Interval (m <sup>3</sup> /s)	Flow Duration in interval (%)	Interval Midpoint (m <sup>3</sup> /s)	Sediment Rating TSS (mg/L)	Sediment Transported (t/a)	Sediment Transported (%)
> 117	0.56	176	68	1,755	0.05%
> 235	6.53	294	175	40,062	1.18%
> 352	16.22	411	324	164,196	4.84%
> 470	14.33	528	514	219,789	6.48%
> 587	16.19	646	743	357,868	10.56%
> 705	13.00	763	1010	400,082	11.80%
> 822	12.47	881	1314	522,191	15.41%
> 939	9.10	998	1654	508,985	15.02%
> 1057	5.61	1116	2029	413,644	12.20%
> 1174	3.16	1233	2439	303,217	8.95%
> 1292	1.34	1350	2883	165,633	4.89%
> 1409	0.52	1468	3360	82,284	2.43%
> 1527	0.70	1585	3871	141,131	4.16%
> 1644	0.27	1703	4414	68,398	2.02%
Sum				3,389,235	

**Table 6. Annual sediment flux of the Kahayan River, determined using sediment rating and flow duration. The sediment rating function is used to determine sediment concentration (column 4) from interval midpoints (column 3). Flow duration within each interval (column 2) is multiplied by sediment concentration to calculate the contribution of each interval.**

Sediment flux estimates derived using this approach range between 100 - 250 t/km<sup>2</sup>/a (Table 7). Mercury flux extrapolations were made using mean TSS mercury measurements from each river class, of 745ng/g and 1171ng/g for the high TSS and low TSS river classes, respectively. Nineteen tonnes of mercury was transported by suspended sediments in these 6 rivers in 2008 (Table 7).

River	Area (km <sup>2</sup> )	Sed flux (t/a)	Sed flux (t/a/km <sup>2</sup> )	Mean Hg concentration (ng/g)	Mercury flux ( t/a)	Mercury flux (g/a/km <sup>2</sup> )
Barito	62,732	6,166,808	98	1,171	7.2	115
Sampit	14,605	1,763,019	121	1,171	2.1	141
Seruyan	12,911	1,271,983	99	1,171	1.5	115
Kapuas	15,836	3,987,856	252	745	3.0	188
Kahayan	15,373	3,389,235	220	745	2.5	164
Katingan	18,982	3,616,352	191	745	2.7	142
Total	140,439	20,195,253	144		19.0	

**Table 7. Annual sediment and mercury flux estimates, for the sampled rivers (flux estimates do not include bed-sediment transport).**

Differences in flux values between within-class rivers originate from the determination of max and min flows for each basin. For example, a higher max precipitation estimate for the Kapuas than the Kahayan is the main reason that estimated fluxes are greater in this basin when basins are normalized to surface area.

These sediment flux estimates incorporate variation in TSS within the hydrograph. Measurement averages have been used as the basis for rating curves and mercury concentrations. These estimates remove sample and temporal bias from the method.

### **3.4.8 Bed Material Transport**

Measurement techniques using acoustic Doppler and echo sounding are increasingly being utilized to make automated measurements of sediment transport bedload processes (Gaeuman and Jacobson 2006); (Nittrouer, Allison et al. 2008). In these and other recent studies, researchers have improved their understanding of how bedloads contribute to sediment flux. Measurements from the lower Mississippi using multibeam profilers (Nittrouer, Allison et al. 2008) provide empirical information regarding sediment transport in large sand bed rivers. Bed-form sand transport rates in the lower Mississippi River are exponentially correlated with discharge, and contribute relatively little to total sediment flux – with bedload transport representing only 2.5% of total suspended sediment transport.

A first approximation estimate of bedload transport was made based loosely on the Mississippi sediment flux relationship (Table 8). Instead of applying the Mississippi figure of 2.5% of total suspended load, a 5% percent proportion was chosen, because hydraulic pumping in these channels is stronger than in the lower Mississippi. Bedload mercury flux was extrapolated from sediment flux and mean measured bulk bedload mercury concentration of 235ng/g (ppb).

River	Area (km <sup>2</sup> )	Suspended Sediment Transport (t/a)	5% of Sediment Transport (t/a)	Bedload Mercury Flux (Hg t/a)
Barito	62,732	6,166,808	308,340	0.072
Sampit	14,605	1,763,019	88,151	0.021
Seruyan	12,911	1,271,983	63,599	0.015
Kapuas	15,836	3,987,856	199,393	0.047
Kahayan	15,373	3,389,235	169,462	0.040
Katingan	18,982	3,616,352	180,818	0.042
Totals	140,439	20,195,253	1,009,763	0.237

**Table 8. Bedload Sediment and Mercury flux, based on 5% of Suspended load transport, and 235ppb bulk bedload mercury concentration.**

### 3.4.9 Bedload Sediment Transport Formulae

Bedload transport formulae have been employed for more than 100 years by engineers and sedimentologists to predict sediment transport rates. Numerous transport formulae have been developed and used, but are often criticized for producing divergent predictions (Batalla, 1997) (Sivakumar and Jayawardena, 2003) and for over-predicting transport rates (Abdel-Fattah, Amin et al. 2004) (Yager, Kirchner et al. 2007). For the current study, several bedload transport equations specifically developed for large lowland sand-bed rivers were investigated. These formulae were developed on the basis of laboratory flume experiments, field measurements, and theoretical predictions. River parameters dictating their applicability include channel width and depth, and sediment size distribution.

Several semi-automated (computer-based) programs have been developed to standardize how sediment transport equations are applied. Three different systems were investigated and employed, with varying degrees of success: the Bureau of Reclamation Automated Modified Einstein Procedure (Holmquist-Johnson, Raff et al. 2009); a Java implemented sediment computing program developed by Venture Lab (VLAB of MIT and Stanford), available at <http://onlinecalc.sdsu.edu/> (Ponce et al., 2009); and the SEDDICH programs developed in the 1980's by the CADGS (Stevens 1985). The results presented below were produced using the SEDDICH program.

The deterministic bed-material formulas of (Laursen and Toch 1956) and (Toffaletti 1968) were chosen based on their applicability to the sampled rivers and the required input parameters. Laursen's formula is based on empirical measurements of natural sediments with a specific gravity of 2.65 and medium diameters that range from 0.011 to 4.08mm. Toffaletti's method is based on the concepts of (Einstein 1942) in which transport is determined from probabilities of particle motion.

Principle input included bedload sediment size fraction data, and channel hydrologic parameters including flow velocity, channel depth, slope, and channel width. Field measurements, GIS, and deductive reasoning calculations were used to produce input parameter sets for each river reach sampled, and for each predicted discharge interval (Table 9).

River	Location	Q (m <sup>3</sup> /s)	mean V (m <sup>3</sup> /s)	Width (m)	Depth (m)	Temp (°C)	D90 (mm)	D65 (mm)	D50 (mm)	D35 (mm)	% bed material small to large size fractions	Slope
Barito	Bangarmasin	4502	0.597	650	11.8	25	0.50	0.19	0.15	0.12	23,40,20,13,4	0.0038
Kapuas	Bangarmasin	1770	0.564	400	8.0	25	0.88	0.45	0.32	0.20	10,22,24,30,14	0.0051
Kahayan	Palangkaraya	771	0.892	150	6.0	25	7.00	1.27	1.00	0.87	1,4,2,18,52,7,1,15	0.0092
Katingan	Kasongan	1279	0.694	275	6.9	25	1.00	0.19	0.13	0.11	30,34,14,11,4,1,6	0.0050
Sampit	Sampit	1431	0.675	295	7.4	25	0.88	0.45	0.32	0.20	2,2,4,13,41,26,12	0.0044
Seruyan	Pembuang	723	0.837	150	6.0	25	3.25	1.63	1.25	0.89	2,2,4,13,41,26,12	0.0149

**Table 9. Sample Input for Bed load transport formulae, used for peak discharge intervals.**

Bedload transport estimates were calculated for each discharge interval, for each sediment size fraction (see Table 10). At low discharge intervals, stream energy was insufficient to move sediments along the bed. On average, predictions of Laursen are greater by a factor of more than 2, with the exception of the Seruyan River, which is larger by factors of 8 (see Table 11). Channel slope and flow velocity appear to increase Laursen's predictions disproportionately, while grain-size has a stronger limiting effect on transport predicted by Toffaleti's formula.

Discharge interval (midpoint, m <sup>3</sup> /s)	Flow Duration (%)	Laursen (t/a)	Toffaleti (t/a)
53	0.56	0	0
106	6.53	0	0
159	16.22	0	163
213	14.33	264	2,547
266	16.19	21,230	6,007
319	13.00	68,270	11,474
372	12.47	119,794	54,173
425	9.10	149,028	19,535
478	5.61	151,329	29,087
531	3.16	125,697	28,550
585	1.34	75,205	17,310
638	0.52	45,474	10,294
691	0.70	82,756	18,824
744	0.27	41,887	9,608
Annual Totals	100	880,934	207,409

**Table 10. Bedload transport formulae results for Kahayan River at Palangkaraya.**

River basin	Basin Area (km <sup>2</sup> )	Mean Flow (m <sup>3</sup> /s)	Laursen (t/a)	Laursen (t/a/Q)	Toffaleti (t/a)	Toffaleti (t/a/Q)
Barito	61,582	4502	1,573,412	349	735,596	163
Sampit	12,360	1431	158,348	111	96,119	67
Seruyan	7,554	723	1,081,869	1,497	138,711	192
Kapuas	13,594	1770	1,095,209	619	363,241	205
Katingan	12,701	1279	1,337,954	1,046	523,387	409
Kahayan	6,958	771	1,113,624	1,445	231,760	301

**Table 11. Laursen and Toffaleti formulae bedload sediment transport predictions.**

On average, the bedload transport rates predicted by Toffaleti and Laursens' formulae are 16±9%, and 62±52% of the sediment rated transport totals (Table 11). Importantly, the use of transport formulae in this context may not adequately constrain sediment source materials. Intense pumping of the hydrologic systems suggests that energy for transport is less of a limiting factor than sediment source constraints. Flux disparity between formulae results weakens confidence in their predictions, and instead

promotes the use of proxy river systems of similar size in the tropics, whose sediment transport systems have been extensively studied. On the basis of comparison with Mississippi system studies (Nittrouer, Allison et al. 2008), the results of Toffaleti's formula appear to provide a more likely representation of reality than Lauren's does.

#### 3.4.10 Total sediment and mercury flux estimates

Entire basin fluxes were determined by summing the sediment rated washload fluxes with estimated bedload fluxes (data is provided in Table 12). Bedload transport proportions were generalized as comprising 5-15% of the washload sediment flux, with a mean of 10%.

Mercury flux extrapolations were made using mean TSS mercury measurements from each river class. These are 745 and 1171ng/g for the high TSS and low TSS river classes, respectively. Average bulk bedload sediment mercury concentration of 235ng/g was applied to the bedload transport sediment mass.

River	Area (km <sup>2</sup> )	TSS transport (t/a)	TSS Hg (Hg ng/g)	TSS Hg flux (Hg t/a)	Bedload transport (t/a)	Bed Hg flux (Hg t/a)	Total sediment flux (t/a)	Total Hg flux (Hg t/a)
Barito	62,732	6,166,808	1,171	7.22	616,681	0.145	6,783,489	7.37
Sampit	14,605	1,763,019	1,171	2.06	176,302	0.041	1,939,321	2.11
Seruyan	12,911	1,271,983	1,171	1.49	127,198	0.030	1,399,181	1.52
Kapuas	15,836	3,987,856	745	2.97	398,786	0.094	4,386,641	3.06
Kahayan	15,373	3,389,235	745	2.52	338,923	0.080	3,728,158	2.60
Katingan	18,982	3,616,352	745	2.69	361,635	0.085	3,977,987	2.78
Total	140,439	20,195,253		18.97	2,019,525	0.475	22,214,778	19.44

**Table 12. Total sediment and mercury flux estimates, based on 2 TSS river classes and bulk bedload Hg of 235ng/g (ppb).**

Bedload mercury flux represents only 2.5% of total river flux in these rivers, despite elemental mercury use and emissions from ASGM in their basins.

#### **3.4.11 Flux estimate uncertainty**

Uncertainty of modelled sediment and mercury fluxes result from four sources: (i) field data and measurement error; (ii) flow discharge uncertainty; (iii) sediment process variability, though the model attempts to accommodate this; and (iv) the use of proxy data from the Berau River discharge dataset, and the TRMM dataset, used for precipitation. Measurement error associated with the mercury analysis was determined statistically to be less than 5%. The other uncertainties, however, could not be statistically derived due to the limited size of the dataset, and therefore it is difficult to apportion uncertainty to modelled fluxes. In spite of this, postulation of expected uncertainty for the estimates presented in this chapter is useful, and is estimated to be  $\pm 35\%$ . Below, this degree of uncertainty is used to establish flux ranges normalized to area for the river basins studied.

On this basis, sediment fluxes normalized to basin size range from 74 to 151 t/km<sup>2</sup>/a for the low TSS river class (Barito, Seruyan, and Sampit rivers), and 143 to 315 t/km<sup>2</sup>/a for the high TSS river class (Kapus, Katingan, and Kahayan rivers). Corresponding riverine mercury transport fluxes range from 87 to 182  $\mu\text{g}/\text{m}^2/\text{a}$ , and 108 to 246  $\mu\text{g}/\text{m}^2/\text{a}$ , respectively. Based on these flux ranges the total mass of mercury transported in the six large rivers ranges between 14.4 and 24.6 tonnes, with a mean of 19.4 tonnes in 2008.

### **3.5 Chapter summary**

Mining operations in Central Kalimantan have a major impact on sediment transport, being capable of increasing sediment loads by factors over 1000 on small tributaries, and doubling sediment loads of major river channels, on average. Flux increases depend more on the type of sediments being mined, than on the number of operations. For example, large dredges on the Barito River which focus on river bed gravels produce far less siltation than smaller dredges processing overbank sediments in the Kahayan River, below which sediment mobilization increased 100-1500 times. Widespread ASGM activities in the Kahayan, Katingan, and Kapuas basins effectively double the main channel sediment flux in these rivers but these effects are diluted in space and time by

mixing. Elevated suspended sediment loads downstream of mining have greater mercury loads per litre of water, but lower mercury concentrations per sediment mass in suspension due to dilution by larger. Mercury flux increases as a result - but not as dramatically as sediment flux, despite the use of mercury at mining operations.

Mercury flux associated with sediment flux in the six large rivers sampled is 19.4 tonnes in 2008. Sediment mercury is dominantly transported (97.5% or 19 tonnes) by suspended sediment and particulates, with the remaining 2.5% (475kg) transported by bedload sediments. Average particulate mercury concentrations of the large rivers sampled in Central Kalimantan were 60.2ng/L (RSD 33%). Another estimated 1.35 tonnes of mercury is transported as dissolved species.

Mercury concentration of bed sediments in the Barito and Kapuas Rivers indicate contamination from decades of heavy mercury use and emission from ASGM around Mount Muro. River sediments analyzed in the region are elevated relative to areas distant from mining by an order of magnitude. Trade winds and climatic events transport volatilized mercury predominantly west and southwards from the Mount Muro emission source, and an unknown fraction of this mercury is re-deposited over watersheds in the Barito, Kapuas, and Kahayan River basins.

The flux of sediments from the six rivers sampled is estimated to be 22.2 million tonnes in 2008. Average sediment concentration of the large rivers sampled in Central Kalimantan was 75mg/L  $\pm$ 58%. Normalized to basin size, the sediment removal rate ranges between 74 and 315 t/km<sup>2</sup>/a, considerably lower than the sediment removal rates postulated for the East Indie Isles by Milliman, Farnsworth et al. (1999), Douglas et al. (1999), Syvitski, Peckham et al. (2003), and Hall and Nichols (2002). These authors predict mean sediment removal rates for the region to be greater than 500 t/km<sup>2</sup>/a, but have not sampled large rivers in Kalimantan. Features of the study area that may help to explain this disparity include low lying topography, relatively intact forests, and sedimentary units cemented by hard clays.

ASGM operations contribute to the mercury load of rivers by increasing suspended sediment loads and associated native mercury, and also by emitting elemental mercury which is used by miners to capture gold. In the first case, mining activities approximately double sediment transport rates on the first order river basins (13,000-63,000km<sup>2</sup>) which increases mercury transport by 50%, on average. Applying this mean to the heavily sedimented rivers of the study area (Kapuas, Kahayan and Katingan), this increase in sediment transport represents between 3 and 5 additional tonnes of sediment associated mercury.

Regarding miners use of elemental mercury, it is difficult to know what proportion of this mercury contributes to particulate associated mercury measured in this thesis. Pristine and impacted streams had similar mercury levels in fine fractions but source apportionment is difficult. Considering that burning of amalgam has been occurring for more than a decade in multiple areas, it is probable that particulate river mercury contains some legacy mercury deposited to the landscape from ASGM, but also from other sources including peat fires. Therefore the proportion of river sediment mercury resulting from ASGM mercury-use is not clearly known. Recall that the annual estimate of mercury used in 2008 is 65.3 tonnes, with 20-30 tonnes emitted to the atmosphere, and 30-40 tonnes released to tailings (from Chapter 2).

## Chapter 4. Improving the ASGM Sector

### 4.1 Development of the ASGM Sector

In Indonesia and elsewhere, development projects are aiming to introduce better practices in the ASGM sector. Globally, the ASGM workforce is estimated to be around 10 million individuals (Telmer and Veiga 2009). This number is a rough estimate but what is more certain is that the number is growing. During the preparation of this thesis, between 2008 and 2011, the gold price doubled from 800 CAD/ozt to above 1,600 CAD/ozt; in the year 2000 the price was only 375 CAD/ozt. Over the last decade, this upwards trend has been the dominant factor increasing the incentive for gold mining, and leading to dramatic rise in the number of artisanal and small-scale gold miners in Indonesia, and elsewhere.

In most regions, miners are not aware of alternative approaches to mercury for extracting gold and/or do not have the economic means to explore these alternatives. Innovation and propagation of mercury free methods requires ASGM operators that are able and interested in exploring mercury-free processing options. Education and assistance for these operators is needed so that mercury-free practices can be locally tailored to regional conditions. History of interventions has shown improvements in practice will occur if these improvements are accompanied by increased gold recovery and/or cost savings. In short, increasing local wealth may be the most important factor required to convince miners to adopt new (mercury reducing or mercury-free) practices. Better policy and effective enacting mechanisms including fair, and accessible mining permit processes; government involvement in gold trading chains; sector oversight; etc. are critical for making the ASGM sector more receptive to the introduction of new practices, including mercury reduction and sedimentation abatement.

Mercury can be a useful contact point for building relationships with ASGM operators and their communities. Through awareness building and education, trust and mutual

concern can be built around the issue of mercury and community health. Once relationships are formed, mercury reducing or mercury free technologies can be introduced to interested operators who become entrepreneurs within their communities. Development programs focusing on reducing mercury emissions are likely to have a better chance of gaining traction in ASGM communities than mercury elimination programs. This is because entrenched behaviors are difficult to change and because supportive, participatory relationships are needed to support operators who are willing to change their process workflows. In this way, mercury reduction programs can provide an important step towards mercury elimination.

Three approaches for reducing and eventually eliminating mercury use are: (i) improving *how* mercury is used in order to reduce consumption, emissions and exposure; (ii) improving the concentration stage of ore processing in order to avoid whole-ore amalgamation and/or reduce the amount of concentrate requiring leaching or amalgamation; and (iii) introducing alternative technologies which do not use mercury. Positive developments in the ASGM sector will be much more likely to succeed if progress is concurrently made towards formalization of mining activities, such that individuals that work in the sector have the opportunity to develop pride in their livelihood.

## **4.2 Improving how mercury is used in Central Kalimantan**

Several promising improvements have been made in Central Kalimantan over the past few years to improve how mercury is being used, and are briefly introduced here.

### **4.2.1 Retorts**

Retorts are devices that can be used to trap mercury fumes from amalgam when it is being heated. Because mercury vapor will condense on any cool surface, heating amalgam in a retort – which is typically an enclosed vessel with a nozzle, works quite well for recapturing elemental mercury during amalgam burning. Retorts can be made

in a wide variety of shapes and sizes, and should be constructed with end-user involvement – in order to suite local amalgam burning habits and needs.

Although mercury retorts were introduced to miners in the Galangan mining area between 2005 and 2006, they were not widely adopted for several reasons: (i) only small balls of amalgam (5-10 grams) were being heated by miners in Galangan, and the retorts were better suited for larger amounts (500g-2kg) of amalgam; (ii) retorting takes longer and re-capture of small amounts of mercury was not worth the additional effort, making the economic return insignificant; (iii) retorts did not allow miners to see the amalgam being burned, and they were uncomfortable with this; (iv) recovering reusable mercury requires some work. These issues regarding the use of retorts are not restricted to the Indonesian context; many development projects have struggled to convince miners to adopt retorts. In the case of point four above, recovering clean liquid mercury from retort water in which mercury is floured (shown in photo below) is best achieved by adding a salt to the water and agitating, to encourage flocculation and precipitation, followed by mercury re-activation – explained below in section 4.2.3.



**Photo Panel 54. (left) Stainless steel retort used in Kering Pangi to recover mercury from amalgam burning roasting; mercury collects in plastic vessel with water seen in the photo. (right) sponge gold, produced by heating amalgam inside the retort.**

Although retorts were not being used by operators visited in the Mount Muro area during the survey in 2008, subsequent visits have confirmed that retort use is becoming

commonplace and that retort designs are being adapted and constructed to meet local needs. Sumali Agrawal (an acquaintance who works with Yayasan Tambuka Sinta) and Dr. Kevin Telmer (supervisor of this thesis) returned to Mount Muro in 2010 as part of a development project to encourage mercury re-capture.

Large steel retorts shown in Photo Panel 55 are used to heat 5-20kg of amalgam at a time. They consist of a large burning chamber, a pipe nozzle and a lid. To operate, the retort with amalgam inside is placed over a gas burner. As the amalgam warms, liquid mercury melts from the amalgam and exits from the pipe. As mercury content of the hot amalgam decreases, mercury exits the retort as vapor. Most of the vapor fraction is not captured with this retort design. In some cases, the pipe end is placed under water so that exiting mercury vapor must bubble through the water as it leaves the retort. This cools the vapor so that additional mercury condenses, and falls into the water. However this outcome is difficult to achieve without complications caused by a vacuum produced inside the retort when it cools. Testing is required to assess the efficacy of these large capacity retorts, but mercury capture is estimated to be 50%.



**Photo Panel 55. Large retorts used for burning 10-20kg of mercury around Mount Muro, photographed by YTS in 2009 (photo credit to Sumali Agrawal).**

#### 4.2.2 Water-trap condenser for use with fumehood

A different system for mercury recovery was developed for use by gold shops in Kereng Pangsi in 2007, after it was determined that more than half of mercury emissions regionally were being released in the village at gold shops (Global Mercury Project, 2006). By working with local operators, a mercury trap was designed as an add-on to existing wooden fumehoods which are used in all of the gold shops. The fumehoods are used to heat balls of amalgam by blow torch numerous times each day. The fumehoods have small chimneys which deliver mercury fumes to the shop roof or out a wall to be emitted into the street. The mercury trap add-on is built from a plastic tub, some plumbing fixtures, and an electric blower fan (Photo panel 56). As mercury vapors are sucked through the water-trap, it cools, making the mercury condense. Mercury collects under the water and can later be collected for resale, providing a monetary incentive for adopting the technology. During the survey in 2008, approximately one year after the apparatus was refined through collaboration with gold shop operators, all 29 of the gold shops in Kereng Pangsi were using the devices. Field tests conducted by the candidate suggest the system captures 65-75% of mercury released during amalgam burning.



Photo Panel 56. (left) Water trap mercury capture system consists of electric blower fan, a clear plastic vessel, and some plumbing fixtures; (right) An installed water trap being used in a gold shop (the water-trap is on the shelf, concealed by a piece of wood).

### 4.2.3 Mercury Re-activation

A third approach capable of significantly reducing mercury consumption in Central Kalimantan and elsewhere is mercury re-activation. After mercury is used for amalgamation, an oxide skin forms on it which often becomes contaminated with other metals, making it less effective for successive amalgamation cycles. This also makes it more apt to flouting- as tiny mercury droplets which become lost to tailings because the oxide coatings increase their surface tension to the point where tiny mercury droplets do not coalesce with other mercury droplets. A similar problem occurs when mercury is collected using water traps as described above, resulting in grey water with suspended mercury particles. Shop owners can add small amounts of soap (to reduce surface tension) or salt (increase the ionic strength of solution to cause flocculation) to help mercury droplets coalesce.

Miners are aware when their dirty mercury has become less effective, but often do not know how to clean it. The simplest way to clean mercury is by passing it through a pinhole filter, which effectively removes the thin oxide coating. Alternatively mercury can be activated (charged) which improves its capacity for amalgamating gold particles. This is done by creating a sodium-mercury amalgam, a strong reducing agent. As such it is able to reduce oxides; this is useful because oxides tend to interfere with amalgamation by covering surfaces of gold particles and mercury.

Re-activating mercury should be done immediately before amalgamation to ensure minimum mercury use and maximum gold recovery. Re-activation is a simple process which can be done using a battery, two wires, a piece of graphite and salt water (or water with caustic soda (NaOH)). The method works fastest using a car or motorcycle battery, but works using small common batteries as well.

Sodium-mercury amalgam is formed by creating a simple electrolytic cell. The method is called the Pantoja Process, the same process used to make chlorine. Mercury is placed in a non-conducting vessel, and covered with a (1:10) salt water solution. Two copper wires are attached to the battery. The negative terminal is connected to the mercury

and the positive terminal is attached to the graphite which is placed in the salt solution. As current passes from the battery through the electrolyte solution, sodium is deposited into the mercury forming a sodium-mercury amalgam- also known as activated or charged mercury. It should be used immediately or stored safely under water, as activated mercury will discharge over time.

The three approaches just reviewed: retorts, water-trap condensers, and mercury re-activation are capable of significantly reducing ASGM mercury emissions in Central Kalimantan. It is important to note, however, that these techniques and devices do not necessarily reduce the risk of acute or prolonged mercury exposure for operators and their families who work and live in close proximity mercury use. As an example, a shop operator who transports a used mercury retort in his car will contaminate the inside of his car with mercury fumes. This is due to mercury's high vapour pressure and its propensity to condense on surfaces. This example highlights the importance of education and awareness-raising alongside mercury reducing technologies.

### **4.3 Improving the concentration stage of ore processing**

Improving concentration represents the largest opportunity to reduce mercury emissions, and a critically important opportunity to empower small-scale operators. This is because the largest mercury emitters – miners practicing whole-ore amalgamation, are not concentrating their ore prior to adding mercury - generally because concentrating these ores efficiently without sophisticated technology is very difficult.

Educating miners regarding how to improve concentration is a critical step to preventing the continual consumption and emission of un-necessarily large amounts of mercury. Concentration approaches depend on the properties of the ore being processed, and what resources are available to the operator. Some of the ways concentration can be improved include: (i) improving gold liberation by crushing and grinding prior to concentration; (ii) making improvements to sluice box design, water management and other basic operating methods; (iii) utilizing enhanced gravity devices such as

centrifuges or shaker tables, to enhance the concentration process; and/or (iv) by introducing another technology such as a floatation cell - useful for sulphidic ores, to the ore-concentration workflow. Descriptions of these technologies are not provided in this thesis, but can easily be obtained in publications or on the internet.

#### **4.4 Alternative leaching technologies**

Numerous alternative mercury-free leaching technologies have potential to be utilized by small-scale gold miners. These include cyanide, electro-oxidation, thiosulphate, bromide, hypochloride, chlorate, and others. The application of these leaching methods requires a higher degree of technical competency relative to amalgamation with mercury, but they often recover more gold. Principle considerations for determining an appropriate leaching technology for particular ASGM situations are: (i) leach process complexity including equipment requirements, technical training necessary, including literacy requirements; (ii) hazard management – relating to toxicity, plan for waste management, access to safety equipment and support, etc; and (iii) process duration – level of urgency for return on capital.

#### **4.5 Reducing sedimentation and improving mine site management**

Reducing sedimentation and improving mine site management represent difficult challenges for ASGM. Sedimentation is a serious concern for miners in Central Kalimantan, and other ASGM regions in Indonesia and abroad. Mobilized sediments alter river channels dramatically and contaminate downstream habitat which can present major problems for downstream river communities. The problem of sedimentation is often recognized by these communities synonymously with mercury contamination despite the fact that sediment hosted mercury may not be a serious threat. As a result, non-mining communities downstream are often at odds with mining populations. In this way ASGM sedimentation has instigated several recent conflicts in Indonesia, as well as Peru, Columbia, Bolivia, and elsewhere.

The siltation problem results from miners operating directly in and adjacent to stream and river channels. This practice was widespread in the late 19<sup>th</sup> century and early 20<sup>th</sup> century in the Caribou Region of British Columbia. Precious little can be done to reduce the effects of river dredging (sluice mining directly in river channels) save outlawing the practice, as was eventually done in BC. There are, however, methods which can be utilized to reduce sedimentation, and remediate mine sites. These include the use of settling ponds to reduce siltation of stream channels; the use of sediment barriers to manage tailings and refill old pits; and dedicated soil capping and tree nursery work for reforesting refilled pits and degraded areas. The work of Rodolfo deSousa (Sousa and Veiga 2008) is based on numerous years of development work with ASGM in the Brazilian Amazon. It documents the implementation of these approaches made in collaboration with ASGM operators, to improve and remediate pit mining of buried alluvials, not unlike those explained in Chapter 2 (Photo panel 57, left). Refilling pits was identified by Sousa and Veiga (2008) as the most important phase of reclamation (Photo panel 57, right). Once the pits are refilled they can be capped with soil or left to re-vegetate on their own.



**Photo Panel 57. ASGM pits are refilled with sediments in the Brazilian Amazon using barriers made from branches and palms, and by positioning sluice boxes in a planned manner.**

## **4.6 Formalization and enforcement**

The application of enforcement mechanisms as a means of improving practices in ASGM is commonly suggested, but very few real-world cases of successful enforcement strategies are known. On the contrary, cases of improved mine management emerge from successful operators and business people who improve their operations as a result of pride in their work and their land, and through the recognition that well run and efficient operations are more profitable. Legal status is often an important factor contributing to this pride. This is because the ASGM sector is comprised of legal, but also numerous informal (partly legal), and illegal individuals and businesses who receive little or no services from government or law enforcement. In Central Kalimantan and elsewhere, formalization of the ASGM sector (legalization of mine sites), represents a key step towards improving small-scale mining practices. Most small-scale miners are financially marginalized and do not operate with flexible profit margins; for these miners, financial costs and monetary incentives dictate how they behave and operate. This important fact must be taken into account in the development of effective state-wide or regional formalization strategies.

## **4.7 Chapter summary**

The focus of ASGM sector development and intervention efforts in Central Kalimantan should be eradication of whole ore amalgamation. It is possible for miners exploiting hard rock ores - including the ones described around Mount Muro, to avoid whole ore amalgamation by improving gold liberation and concentration, and using processes other than mercury for leaching. Alternatively, or until this conversion can be fully realized, ASGM operators can reduce mercury consumption and emissions dramatically by improving how mercury is being used, through the use of retorts, fumehoods, and re-activation cells.

## Bibliography

- Abdel-Fattah, S., A. Amin, et al. (2004). Sand transport in Nile River, Egypt. Journal of Hydraulic Engineering **130**: 488.
- Adler, R., S. Braun, et al. (2007). Tropical Rainfall Measuring Mission, TRMM, Senior Review Proposal.
- Artaxo, P., R. Calixto de Campos, et al. (2000). Large scale mercury and trace element measurements in the Amazon basin. Atmospheric Environment **34**(24): 4085-4096.
- Asselman, N. E. M. (1999). Suspended sediment dynamics in a large drainage basin: the River Rhine. Hydrological Processes **13**: 1437-1450.
- Ayhuan, D., O. Atteng, et al. (2003). Mercury pollution on district of Dimembe river system, North Sulawesi, Indonesia, due to traditional gold mining activities. Science of the Total Environment **107**: 79-82.
- Batalla, R. J. (1997). Evaluating Bed material Transport Equations using Field Measurements in a Sandy Gravel bed Stream, Arbúcies River, NE Spain. Earth Surface Processes and Landforms **22**(2): 121-130.
- Bonell, M. and L. A. Bruijnzeel (2004). Forests, water, and people in the humid Tropics: past, present, and future hydrological research for integrated land and water management, Cambridge Univ Pr.
- Brodjonegoro, B. and J. F. G. Ford (2007). Intergovernmental Fiscal Relations and State Building: The Case of Indonesia, Edward Elgar Pub: 320.
- Carlile, J. C. and A. H. G. Mitchell (1994). Magmatic arcs and associated gold and copper mineralization in Indonesia. Journal of Geochemical Exploration **50**(1-3): 91-142.
- Clarkson, T. W. and L. Magos (2006). The toxicology of mercury and its chemical compounds. Critical Reviews in Toxicology **36**(8): 609-662.
- Clifton, II and C. Jack (2007). Mercury exposure and public health. Pediatric Clinician North America **54**(2): 237.
- Coelho-Souza, S. A., J. R. D. Guimaraes, et al. (2006). Mercury methylation and bacterial activity associated to tropical phytoplankton. Science of the Total Environment **364**(1-3): 188-199.

- Costa, M. H., C. H. C. Oliveira, et al. (2002). A macroscale hydrological data set of river flow routing parameters for the Amazon Basin. Journal of Geophysical Research **107**: 8039.
- Douglas, I., K. Bidin, et al. (1999). The role of extreme events in the impacts of selective tropical forestry on erosion during harvesting and recovery phases at Danum Valley, Sabah. Philosophical Transcriptions of the Royal Society of London **354**(1391): 1749.
- Douglas, I., T. Spencer, et al. (1992). The impact of selective commercial logging on stream hydrology, chemistry and sediment loads in the Ulu Segama rain forest, Sabah, Malaysia. Philosophical Transcriptions of the Royal Society of London: 397-406.
- Downs, S. G., C. L. Macleod, et al. (1998). Mercury in Precipitation and Its Relation to Bioaccumulation in Fish: A Literature Review. Water Air Soil Pollution **108**(1): 149-187.
- Eckley, C. S., M. Gustin, et al. (2010). Measurement of surface mercury fluxes at active industrial gold mines in Nevada (USA). Science of the Total Environment.
- Ehrlich, H. L. and D. K. Newman (2009). Geomicrobiology, CRC.
- Einstein, H. A. (1942). Formulas for the transportation of bed load. **107**: 561–597.
- United States Environmental Protection Agency Office of Water (2001) Guidance for Implementation and Use of EPA Method 1631 for the Determination of Low-Level Mercury EPA 821-R-01-023.
- Friedli, H. R., A. F. Arellano, et al. (2009). Initial estimates of mercury emissions to the atmosphere from global biomass burning. Environmental Science and Technology **43**(10): 3507-3513.
- Fujii, K., M. Uemura, et al. (2009). Fluxes of dissolved organic carbon in two tropical forest ecosystems of East Kalimantan, Indonesia. Geoderma **152**(1-2): 127-136.
- Gabriel, M. C. and D. G. Williamson (2004). Principal biogeochemical factors affecting the speciation and transport of mercury through the terrestrial environment. Environmental geochemistry and health **26**(3): 421-434.
- Gaeuman, D. and R. B. Jacobson (2006). Acoustic bed velocity and bed load dynamics in a large sand bed river. Journal of geophysical research **111**(F2):2005.
- George Cherian, M. and R. A. Goyer (1978). Metallothioneins and their role in the metabolism and toxicity of metals. Life Sciences **23**(1): 1-9.

- Gosselin, P. D., B. (2005). Gold Deposits of the World: Distribution, Geological Parameters and Gold Content. Geological Survey of Canada, Open File 4895.
- Govindaswamy, N., J. Moy, et al. (1992). A distorted mercury [Hg (SR) 4] 2-complex with alkanethiolate ligands: the fictile coordination sphere of monomeric [Hg (SR) x] complexes. Inorganic Chemistry **31**(26): 5343-5344.
- Grigal, D. F. (2002). Inputs and outputs of mercury from terrestrial watersheds: a review, NRC Research Press. **10**:1-39.
- Grimaldi, M., Amouroux, D., Grimaldi, C., Spadini, L., Tessier, E., Dutin, G., Sarrazin, M., 2002. Mercury in French Guiana research Program. Final report, part two: the region of high Maroni and the ECEREX watershed, 2. CNRS-PEVS.
- Grimaldi, C. and S. Guedron (2008). Mercury distribution in tropical soil profiles related to origin of mercury and soil processes. Science of the Total Environment **401**(1-3): 121-129.
- Gu, B., Biana, Y., Miller, C., Dong, W., Jiang, X., Liang, L. (2010) Mercury reduction and complexation by natural organic matter in anoxic environments. Environmental Sciences Division and Institute of Soil Science, Chinese Academy of Science.
- Guedron, S., C. Grimaldi, et al. (2006). Weathering versus atmospheric contributions to mercury concentrations in French Guiana soils. Geoderma **21**(11): 2010-2022.
- Guminski, C., Z. Galus, et al. (1986). Solubility Data Series—Metals in Mercury. **25**.
- Gustin, S. M., M. Coolbaugh, et al. (2003). Atmospheric mercury emissions from mine wastes and surrounding geologically enriched terrains. Environmental Geology **43**(3): 339-351.
- Hall, C. A. S. (2000). Quantifying sustainable development: the future of tropical economies, Academic Pr.
- Hall, R. and G. Nichols (2002). Cenozoic sedimentation and tectonics in Borneo: climatic influences on orogenesis. Journal of Asian Earth Sciences **191**(1): 5.
- Hall, R., M. W. A. van Hattum, et al. (2008). Impact of India-Asia collision on SE Asia: the record in Borneo. Tectonophysics **451**(1-4): 366-389.
- Hamilton, W. (1979). Tectonics of the Indonesian region, US Govt. Print. Off. United States Agency for International Development.

- Hansen, D. and D. I. Bray (1993). Single-station estimates of suspended sediment loads using sediment rating curves. Canadian Journal of Civil Engineering **20(1)**: 133–143.
- Hedgecock, I. M. and N. Pirrone (2004). Chasing quicksilver: Modeling the atmospheric lifetime of Hg<sup>0</sup> (g) in the marine boundary layer at various latitudes." Environmental science and technology **38(1)**: 69-76.
- Hoitink, A. J. F., F. A. Buschman, et al. (2009). Continuous measurements of discharge from a horizontal acoustic Doppler current profiler in a tidal river. Water Resources Research **45(11)**:11406.
- Holmquist-Johnson, C., D. A. Raff, et al. (2009). Bureau of Reclamation Automated Modified Einstein Procedure (BORAMEP) Program for Computing Total Sediment Discharge.
- Horowitz, A. J. (2003). An evaluation of sediment rating curves for estimating suspended sediment concentrations for subsequent flux calculations. Hydrological processes **17(17)**: 3387-3409.
- Hylander, L. D. and M. Meili (2003). 500 years of mercury production: global annual inventory by region until 2000 and associated emissions. Science of the Total Environment **304(1-3)**: 13-27.
- Jansson, M. B. (1996). Estimating a sediment rating curve of the Reventazon river at Palomo using logged mean loads within discharge classes. Journal of Hydrology **183(3-4)**: 227-241.
- Kaiser, K. and W. Zech (1998). Rates of dissolved organic matter release and sorption in forest soils. Soil Science **163(9)**: 714.
- Kobiela, T., B. Nowakowski, et al. (2003). The influence of gas phase composition on the process of Au-Hg amalgam formation. Applied Surface Science **206(1-4)**: 78-89.
- Lacerda, L. D., M. G. Ribeiro Jr, et al. (1999). Atmospheric Deposition to Northern South America during the Last 1000 Years. Conference Proceedings **65**.
- Laursen, E. M. and A. Toch (1956). Scour around bridge piers and abutments, Iowa Inst. of Hydraulic Research.
- Levlin, M., H. E. M. Niemi, et al. (1996). Mercury adsorption on gold surfaces employed in the sampling and determination of vaporous mercury: a scanning tunneling microscopy study. Journal of Analytical Chemistry **355(1)**: 2-9.

- MacDonald, R. (2011). The trouble with Hg - an oceanographer's perspective, Oral Presentation. University of Victoria, Department of Earth and Ocean Science.
- Malmer, A. (1990). Stream suspended sediment load after clear-felling and different forestry treatments in tropical rainforest, Sabah, Malaysia. Research Needs and Applications to Reduce Erosion and Sedimentation in Tropical Stecplands (Proceedings of the Fiji Symposium, June 1990), IAHS-AISH Publ. No.192.
- Manaf, H. (1999). The Environmental Impact of Small Scale Mining in Indonesia.
- Marengo, J. A. (2005). Characteristics and spatio-temporal variability of the Amazon River Basin Water Budget. Climate Dynamics **24**(1): 11-22.
- Marxsen, J., H. H. Schmidt, et al. (1997). Organic matter dynamics in the Breitenbach, Germany. Journal of the North American Benthological Society **16**(1): 28-32.
- Mason, R. P., W. F. Fitzgerald, et al. (1994). The biogeochemical cycling of elemental mercury: anthropogenic influences. Geochimica et Cosmochimica Acta **58**(15): 3191-3198.
- Mauro, J., J. Guimaraes, et al. (2002). Mercury methylation in macrophytes, periphyton, and water-comparative studies with stable and radio-mercury additions. Anal. of Bioanalytical Chemistry **374**(6): 983-989.
- Melamed, R., R. C. Villas Bôas, et al. (1997). Mechanisms of physico-chemical interaction of mercury with river sediments from a gold mining region in Brazil: Relative mobility of mercury species. Journal of Geochemical Exploration **58**(2-3): 119-124.
- Metcalfe, I. (1996). Pre-Cretaceous evolution of SE Asian terranes. Special Publication **106**(1): 97.
- Milliman, J. D., K. L. Farnsworth, et al. (1999). Flux and fate of fluvial sediments leaving large islands in the East Indies. Journal of Sea Research **41**(1-2): 97-107.
- Milliman, J. D. and R. H. Meade (1983). World-wide delivery of river sediment to the oceans. Journal of Geology **91**(1): 1-21.
- Milliman, J. D. and J. P. M. Syvitski (1992). Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers. Journal of Geology **100**(5): 525-544.
- Miranda, M. R., J. R. D. Guimaraes, et al. (2004). Mercury methylation and bacterial activity in macrophyte-associated periphyton in floodplain lakes of the Amazon basin, RMZ-Materials and Geo-environment. **51**: 1218-1220.

- Mol, J. H. and P. E. Ouboter (2004). Downstream Effects of Erosion from Small Scale Gold Mining on the Instream Habitat and Fish Community of a Small Neotropical Rainforest Stream. Conservation Biology **18**(1): 201-214.
- Moss, S. J. and M. E. J. Wilson (1998). Biogeographic implications of the Tertiary palaeogeographic evolution of Sulawesi and Borneo. Biogeography and Geological Evolution of SE Asia, Backhuys: 133–163.
- Mossa, J. (1996). Sediment dynamics in the lowermost Mississippi River. Engineering Geology **45**(1-4): 457-479.
- Nagle, G. Management of Sedimentation in Tropical Watersheds Environmental Management **23** (4): 441–452.
- Nakazono, E. M., B. R. Fosberg, et al. (1999). Factors controlling mercury contamination in tucunarés (*Cichla* sp.) from the Negro and Tapajós river basins, Brazilian Amazon. Science of the total environment **212**.
- Nittrouer, J. A., M. A. Allison, et al. (2008). Bedform transport rates for the lowermost Mississippi River. Journal of Geophysical Research **113**(F3): F03004.
- Palmer, C. and S. Engel (2007). For better or for worse? Local impacts of the decentralization of Indonesia's forest sector. World Development **35**(12): 2131-2149.
- Ravichandran, M. (2004). Interactions between mercury and dissolved organic matter--a review. Chemosphere **55**(3): 319-331.
- Roulet, M., Lucotte, M., Saint-Aubina, A., Tran S., Rheault, I., Farella, N., De Jesus Da silva, E., Dezencourt J., Sousa Passos, C-J., Santos Soares, G., Guimaraes, J., Mergler, D., Amorime M. (1998) The geochemistry of mercury in central Amazonian soils developed on the Alter-do-Chao formation of the lower Tapajos River Valley, Para state, Brazil The Science of the Total Environment **223**(24).
- Roulet, M., J. R. D. Guimaraes, et al. (2001). Methylmercury production and accumulation in sediments and soils of an Amazonian floodplain--effect of seasonal inundation. Water Air Soil Pollution **128**(1): 41-60.
- Satyana, A. H., D. Nugroho, et al. (1999). Tectonic controls on the hydrocarbon habitats of the Barito, Kutei, and Tarakan Basins, Eastern Kalimantan, Indonesia: major dissimilarities in adjoining basins. Journal of Asian Earth Sciences **17**(1-2): 99-122.

- Schroeder, W. H. and J. Munthe (1998). Atmospheric mercury--an overview. Atmospheric Environment **32**(5): 809-822.
- Schuster, E. (1991) The behavior of the mercury in the soil with special emphasis on complexation and adsorption processes; a review of the literature. Water, air and soil pollution **56**() 667 -680.
- Schumacher, B. A. (2002). Methods for the determination of total organic carbon (TOC) in soils and sediments, Ecological Risk Assessment Support Center, Office of Research and Development, US Environmental Protection Agency, Las Vegas.
- Seeley, J. B. and T. J. Senden (1994). Alluvial gold in Kalimantan, Indonesia: A colloidal origin? Journal of Geochemical Exploration **50**(1-3): 457-478.
- Sholupov, S. E. and A. A. Ganeyev (1995). Zeeman atomic absorption spectrometry using high frequency modulated light polarization. Atomic Spectroscopy **50**(10): 1227-1236.
- Simmons, S. F. and P. R. L. Browne (1990). Mineralogic, alteration and fluid-inclusion studies of epithermal gold-bearing veins at the Mt. Muro Prospect, Central Kalimantan (Borneo), Indonesia. Journal of Geochemical Exploration **35**(1-3): 63-103.
- Sivakumar, B. and A. W. Jayawardena (2003). Sediment transport phenomenon in rivers: an alternative perspective. Environmental Modelling & Software **18**(8-9): 831-838.
- Slowey, A. J., J. J. Rytuba, et al. (2005). Speciation of mercury and mode of transport from placer gold mine tailings, ACS Publications. **39**: 1547-1554.
- Smith, C. N., S. E. Kesler, et al. (2008). Isotope geochemistry of mercury in source rocks, mineral deposits and spring deposits of the California Coast Ranges, USA. Earth and Planetary Science **269**(3-4): 399-407.
- Sousa, R. N. and M. M. Veiga (2008). Garimpo Canaan: a successful case of reclamation of an artisanal gold mine in the Amazon. British Columbia Mine Reclamation Symposium 2008.
- Stevens, H. H. (1985). Computer program for the computation of total sediment discharge by the modified Einstein procedure.
- Sunderland, E. M. and R. P. Mason (2007). Human impacts on open ocean mercury concentrations. Global Biogeochemical Cycles **21**(4).

- Syvitski, J. P. M., S. D. Peckham, et al. (2003). Predicting the terrestrial flux of sediment to the global ocean: a planetary perspective. Sedimentary Geology **162**(1-2): 5-24.
- Telmer, K., M. Costa, et al. (2006). The source and fate of sediment and mercury in the Tapajos River, Para, Brazilian Amazon: ground-and space-based evidence. Journal of Environmental Management **81**(2): 101-113.
- Telmer, K. and D. Stapper (2007). Evaluating and Monitoring Small Scale Gold Mining and Mercury Use: Building a Knowledge-base with Satellite Imagery and Field Work. UNIDO Project EG/GLO/01/G34.
- Telmer, K. H. and M. M. Veiga (2009). World emissions of mercury from artisanal and small scale gold mining. Mercury Fate and Transport in the Global Atmosphere, Springer: 131-172.
- Thompson, J. F. H., H. Z. Abidin, et al. (1994). Alteration and epithermal mineralization in the Masupa Ria volcanic center, Central Kalimantan, Indonesia. Journal of Geochemical Exploration **50**(1-3): 429-456.
- Toffaleti, F. B. (1968). A Procedure for Computation of the Total River Sand Discharge and Detailed Distribution, Bed to Surface, Committee on Channel Stabilization (US Army).
- Ullrich, S. M., T. W. Tanton, et al. (2001). Mercury in the aquatic environment: a review of factors affecting methylation. Critical Reviews in Environmental Science and Technology **31**(3): 241-293.
- Van Leeuwen, T. M. (1994). 25 years of mineral exploration and discovery in Indonesia. Journal of Geochemical Exploration **50**(1994): 13-90.
- Van Leeuwen, T. M., T. Leach, et al. (1990). The Kelian disseminated gold deposit, east Kalimantan, Indonesia. Journal of Geochemical Exploration **35**(1-3): 1-61.
- Veiga, M. M., J. Hinton, et al. (1999). Mercury in the Amazon: a comprehensive review with special emphasis on bioaccumulation and bioindicators. Proceedings from the National Institute for Minamata Disease Forum, 1999. Minamata, Japan. **99**: 19-39.
- von Tumpling, W., R. D. Wilken, et al. (1996). Mercury Deposition Resulting from Setting on Fire of Grasslands-Estimation of the Annual Mercury Deposition of the Tropical Northern Pantanal Region, Central Brazil. Journal of Geochemical Exploration. **58** (2-3): 223-22.

- Whitehouse, A. E., H. H. Posey, et al. (2006). Mercury discharges from small scale gold mines in North Sulawesi, Indonesia: Managing a change from mercury to cyanide. 7th International Conference on Acid Rock Drainage (ICARD). St. Louis MO. **26**: 2354-2368.
- Yang Y., Li, L., Dingyong, W. (2008) Effect of dissolved organic matter on adsorption and desorption of mercury by soils Journal of Environmental Sciences, China **20** (9) 1097-1102.
- Yager, E. M., J. W. Kirchner, et al. (2007). Calculating bed load transport in steep boulder bed channels. Water Resources Research **43**(7):7418.
- You, S. J., Y. Yin, et al. (1999). Partitioning of organic matter in soils: effects of pH and water/soil ratio. Science of the Total Environment **227**(2-3): 155-160.