

Bielefeld University
School of Public Health

**MERCURY USE IN ARTISANAL SMALL-SCALE GOLD MINING
THREATENS HUMAN HEALTH**

Measures to describe and reduce the health risk

Cumulative Dissertation Thesis

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By

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Es ist nicht deine Schuld, dass die Welt ist wie sie ist.

Es wäre nur deine Schuld, wenn sie so bleibt.

[It is not your fault that the world is the way it is. It would, however, be your fault if you allowed it to remain that way.] Urlaub, Farin [Jan Ulrich Max Vetter]. 2003. Deine Schuld. In: Die Ärzte. Geräusch, CD 2, track 2 (2 CDs). Hot Action Records (Berlin, Germany).

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Abbreviations

µg/l	Microgram per liter
µg/g	Microgram per gram
ASG	Artisanal small-scale gold
ASGM	Artisanal small-scale gold mining
Au	<i>Aurum</i> (Gold)
B ₄ Na ₂ O ₇ ·10H ₂ O	Sodium tetraborate (borax)
BAT	<i>Biologischer Arbeitsplatztoleranzwert</i> (Biological workplace tolerance level)
BoD	Burden of disease
CMMVI	Chronic metallic mercury vapor intoxication
cr.	Creatinine
CRA	Comparative Risk Assessment
DALY	Disability-adjusted life year
DFG	<i>Deutsche Forschungsgemeinschaft</i> (German Research Foundation)
DisMod II	Disease model, second version, software tool developed by the World Health Organization
DiWIntox	Disability weights for chronic mercury intoxication
DW	Disability weight
EBD	Environmental burden of disease
EQ-5D+C-3L	EuroQol questionnaire with 5 dimensions (mobility, self-care, usual activities, pain/discomfort, anxiety/depression) accompanied by the cognition add-on questionnaire, coded in 3 levels for responses (1: no problems; 2: problems; 3: severe problems)
GBD	Global burden of disease
GEF	Global Environment Facility
GMP	Global Mercury Project
HBM	Human biomonitoring
HBM I, HBM II	Human biomonitoring values I and II from the human biomonitoring commission of the German Environment Agency
Hg	<i>Hydrargyrum</i> (Mercury)

HIA	Health impact assessment
HRQoL	Health-related quality of life
IF	Impact fraction
LMU	Ludwig-Maximilians-University Munich
LOD	Level of detection
MMR	Mild mental retardation
MoH	Mongolian Ministry of Health
MOT	<i>Motoriktest</i> (Motor proficiency test developed by Zimmer and Volkamer 1984)
NAG	N-acetyl- β -glucosaminidase
P	Published scientific papers included in this thesis
PAF	Population attributable fraction
SMPH	Summary measure of population health
t/a	Tons per annum
UMIT	Austrian University of Health Sciences, Medical Informatics and Technologies
UNIDO	United Nations Industrial Development Organization
WHO	World Health Organization
YLD	Years lived with disability
YLL	Years lost due to premature mortality

List of published scientific papers forming the basis of this thesis

- P1: Bose-O'Reilly S, McCarty KM, **Steckling N**, Lettmeier B. Mercury exposure and children's health. *Current Problems in Pediatric and Adolescent Health Care*. 2010;40(8):186-215. Access: [http://www.cppah.com/article/S1538-5442\(10\)00093-3/pdf](http://www.cppah.com/article/S1538-5442(10)00093-3/pdf). *Impact Factor: 1.560*
- P2: **Steckling N**, Boese-O'Reilly S, Gradel C, Gutschmidt K, Shinee E, Altangerel E, Badrakh B, Bonduush I, Surenjav U, Ferstl P, Roider G, Sakamoto M, Sepai O, Drasch G, Lettmeier B, Morton J, Jones K, Siebert U, Hornberg C. Mercury exposure in female artisanal small-scale gold miners (ASGM) in Mongolia: An analysis of human biomonitoring (HBM) data from 2008. *Science of the Total Environment*. 2011;409(5):994-1000. Access: <http://www.sciencedirect.com/science/article/pii/S004896971001260X>. *Impact Factor: 3.163*
- P3: **Steckling N**, Bose-O'Reilly S, Pinheiro P, Plass D, Shoko D, Drasch G, Bernaudat L, Siebert U, Hornberg C. The burden of chronic mercury intoxication in artisanal small-scale gold mining in Zimbabwe: data availability and preliminary estimates. *Environmental Health*. 2014;13:111. Access: <http://www.ehjournal.net/content/13/1/111>. *Impact Factor: 2.71*
- P4: **Steckling N**, Plass D, Bose-O'Reilly S, Kobal AB, Krämer A, Hornberg C. Disease profile and health-related quality of life (HRQoL) using the EuroQol (EQ-5D+C) questionnaire for chronic metallic mercury vapor intoxication. *Health and Quality of Life Outcomes*. 2015;13:196. Access: <http://hqlo.biomedcentral.com/articles/10.1186/s12955-015-0388-0>. *Impact Factor: 2.10*
- P5: **Steckling N**, Bose-O'Reilly S, Shoko D, Muschack S, Schierl R. Testing Local Conditions for the Introduction of a Mercury-free Gold Extraction Method using Borax in Zimbabwe. *Journal of Health and Pollution*. 2014;4(7):54-61. Access: <http://www.journalhealthpollution.org/doi/abs/10.5696/2156-9614-4-7.54>. *Impact Factor: not available.*

Abstract

Background: Mercury is used in more than 70 countries to extract gold in artisanal small-scale gold mining (ASGM). The application of mercury is simple and plays a key role in the livelihood for more than 16 million gold miners. Mercury is added to the crushed ore and builds an amalgam with the gold it contains. The amalgam is then smelted, the mercury evaporates, and gold remains. The amalgam smelting is the main source of mercury exposure in ASGM. ASGM is the largest anthropogenic source of global mercury pollution. The toxic metal poses a risk to the health of both the miners involved and the residents in the area, who do not work in ASGM. Mercury can be detected in critical quantities in the human bodies of both groups. The local threat aside, the mercury released is also of global concern due to its high transportability and persistence in the environment as well as its tendency to bioaccumulate. Mercury is neurotoxic and its harmful effects on the development of unborn children and infants are particularly alarming. Describing and reducing the health risk posed by the mercury used in ASGM are urgently needed measures, as demanded in the 2013 agreed Minamata Convention on Mercury.

Objective and research questions: The overall objective of this thesis is to apply public health measures to describe the health risk due to the use of mercury in selected ASGM areas and to test the feasibility of a mercury-free extraction procedure using borax to reduce the risk. The main research question is: How to describe and reduce the human health risk of mercury used in ASGM? Four subquestions regard (I) the relevance of addressing different subgroups when attempting to describe and reduce the human health risk of mercury used in ASGM, (II) the mercury body burden in ASGM, (III) the health burden due to mercury exposure in ASGM, and (IV) a means of reducing the health risk due to the use of mercury in ASGM. The response to the research questions is included in the present synopsis and based on five published and peer-reviewed scientific papers.

Materials and methods: This thesis comprises different materials and methods. The literature used was searched by applying narrative and systematic approaches (papers P1, P2, P3, P4, P5). P1 is a narrative review about children's health and exposure to mercury. In P2 and P3, the mercury body burden was determined using human biomonitoring (HBM) data collected in Mongolia in 2008 (P2) and Zimbabwe in 2004 and 2006 (P3) and compared with the German HBM values, HBM I and II (P2, P3). Health effects attributable to mercury were analyzed for the sample from Zimbabwe using anamnestic data, neuropsychological testing, and clinical examination (P3). Cases of chronic mercury intoxication were identified and the sample prevalence determined and extrapolated to all of Zimbabwe (P3). The environmental burden of disease

(EBD) was quantified in terms of disability-adjusted life years (DALYs) including primary, secondary, and modeled data (P3). Disease-specific and generic health state descriptions were developed which could be used to derive disability weights (DWs) for disease stages of the intoxication due to exposure to mercury in gold mining. Information about the health-related quality of life (HRQoL) and a comprehensive list of possible symptoms were gathered by expert elicitation. The list of symptoms was supplemented by a systematic literature search (P4). The feasibility of a mercury-free gold extraction method using borax was tested in a field project in Kadoma, Zimbabwe, in 2013 (P5).

Results: Children are particularly vulnerable to mercury exposure. They might be exposed directly and indirectly to it from ASGM while several subgroups (pregnant and breastfeeding women, parents working as miners, etc.) play a role in the children's exposure (P1). In the districts Bornuur and Jargalant, Mongolia, a sample of women of child-bearing age involved in mining or living in mining areas (P2), and in Kadoma, Zimbabwe (P3), a sample of adult and child male and female miners were investigated. Both samples showed raised mercury concentrations in human specimens above health-related exposure limit values. The analyses of health data showed a higher frequency of possibly mercury-related health effects in miners in comparison to controls (P3). The EBD in male and female adult and child miners in Zimbabwe in 2004 was high (total of 95,400 DALYs, 8 DALYs/1,000 population) while subgroup analyses identified males, particularly male children and young male adult workers, as the group with the highest burden (P3). The HRQoL of individuals with chronic metallic mercury vapor intoxication (CMMVI) caused by mercury exposure from ASGM can be substantially reduced by a number of health symptoms of varying severities (P4). In field testing, the application of a mercury-free gold extraction method using borax has been considered as feasible, what could reduce the health risk posed by mercury in ASGM (P5).

Discussion: This thesis provides evidence to improve the understanding of the human health risk due the use of mercury in ASGM. The human health risk posed by mercury in ASGM can be described as *considerable*, *subgroup-specific*, and, indeed, *reducible*. The health risk is *considerable* given the particular risk of children (P1), the high mercury concentrations in specimens obtained from miners and not occupationally exposed residents in ASGM areas (P2, P3), the high prevalence of intoxications and EBD of miners (P3), the extensive range of possible health symptoms, and the reduced HRQoL due to mercury intoxication (P4). The health risk can be considered *subgroup-specific* for several reasons. These include the particular risk to children and the influence which the behavior of other subgroups has on the children's exposure (P1), the human body burden detectable in miners and non-occupationally exposed residents in ASGM

areas varying by sex and age (P2, P3), the prevalence of intoxications and EBD of intoxications in miners varying by sex and age (P3), and the extensive range of possible health symptoms which can but do not have to occur in individuals as a result of exposure to mercury (P3, P4). The health risk is *reducible* with regard to the fact that a mercury-free gold extraction method has been tested successfully (P5). Research of international literature reveals significant differences in mercury concentrations in human specimens of subgroups in ASGM areas. Combining HBM with health data is reasonable for identifying cases of chronic mercury intoxication, has also been done in samples of other countries. Based on the preliminary DALY estimates, chronic mercury intoxication from ASGM was integrated in the top 20 causes of the BoD in Zimbabwe in 2004 as estimated by the World Health Organization (WHO) in the GBD 2004 update. A national estimation of DALYs due the use of mercury in ASGM had not been investigated up to this point. Other DALY quantifications with focus on mercury are available, however, the research gaps for the use of mercury in ASGM (e.g., missing DWs) are mentioned in international literature. Results about the HRQoL of CMMVI enabled comparisons with the HRQoL of other health states investigated in other studies. The mercury-free gold extraction procedure using borax was identified as feasible in ASGM in Kadoma, Zimbabwe, and was also reported from other ASGM areas. However, a sustainable introduction needs follow-up implementation activities. Further main limitations of this thesis are restricted literature search strategies, small sample sizes, and the reliance on assumptions and modeled data. The results of this thesis can be integrated into 8 of 9 steps of a human health risk analysis. Measures used to describe the risk should be applied in a health impact assessment (HIA) to monitor the success of a comprehensive introduction of a mercury-free extraction procedure.

Conclusions: It is the conclusion of this thesis that the human health risk from mercury used in ASGM is *considerable, subgroup-specific, and reducible*. Various materials and methods were used, while some (e.g., estimation of DALYs and determination of HRQoL) had not been applied to this topic before. The relevance of different subgroups in the effort to describe and reduce the risk due to mercury from ASGM was identified. Some subgroups require attention most urgently either due to their particularly high vulnerability (fetuses and children), their influence on the exposure of others (e.g., pregnant women), or their particularly high EBD (young male gold miners). This thesis underlines the necessity to reduce the human health risk due to mercury in ASGM. The results of this thesis should be understood as an impetus to finding solutions for the continuing threat to human health from the use of mercury in ASGM.

Zusammenfassung

Quecksilberverwendung im handwerklichen Kleingoldbergbau als Bedrohung der menschlichen Gesundheit - Maßnahmen zur Beschreibung und Verminderung des Gesundheitsrisikos

Hintergrund: Quecksilber wird weltweit in über 70 Ländern im handwerklichen Kleingoldbergbau für die Goldgewinnung genutzt. Die Quecksilberverwendung ist einfach und sichert die Lebensgrundlage von mindestens 16 Millionen Goldminenarbeitern/innen. Quecksilber wird dem zerkleinerten Erz zugeführt und bildet ein Amalgam mit dem enthaltenen Gold. Dieses wird geschmolzen, so dass das Quecksilber verdampft und das Gold übrig bleibt. Die Verdampfung verursacht die Hauptexposition gegenüber Quecksilber im Goldabbau. Der handwerkliche Kleingoldbergbau stellt die größte anthropogene Quelle der globalen Quecksilberschmutzung dar. Die Gesundheit der involvierten Arbeiter/innen und nicht involvierten Anwohner/innen im Umfeld der Goldbergbaugebiete ist von dem toxischen Metall bedroht, welches in ihren Körpern in kritischen Mengen nachweisbar ist. Neben dieser lokalen Bedrohung stellt das freigegebene Quecksilber eine globale Gefahr dar. Quecksilber ist persistent und verbreitet sich in der Umwelt. Hinzu kommt dessen Fähigkeit zur Bioakkumulation. Quecksilber verursacht insbesondere neurotoxische Effekte, wobei schädigende Einflüsse auf die Entwicklung des (ungeborenen) Kindes besonders besorgniserregend sind. Die Beschreibung und Reduktion des Gesundheitsrisikos der Quecksilberverwendung im handwerklichen Kleingoldbergbau sind dringend erforderliche Maßnahmen, wie in der 2013 vereinbarten Minamata Konvention gefordert.

Ziele und Forschungsfragen: Das übergeordnete Ziel der Dissertation ist die Anwendung von gesundheitswissenschaftlichen Maßnahmen zur Beschreibung des Gesundheitsrisikos der Quecksilberverwendung im handwerklichen Kleingoldbergbau und zur Überprüfung der Machbarkeit einer quecksilberfreien Goldgewinnungsmethode zur Reduktion des Risikos. Die Hauptforschungsfrage lautet: Wie kann das Gesundheitsrisiko durch die Quecksilberverwendung im handwerklichen Kleingoldbergbau beschrieben und reduziert werden? Vier Unterfragen betrachten (I) die Relevanz der Berücksichtigung unterschiedlicher Subgruppen bei der Beschreibung und Reduktion des Gesundheitsrisikos durch die Quecksilberverwendung im handwerklichen Kleingoldbergbau, (II) die Quecksilber-Körperlast im handwerklichen Kleingoldbergbau, (III) die gesundheitlichen Belastung durch Quecksilberexposition im handwerklichen Kleingoldbergbau und (IV) die Möglichkeit der Reduktion des Gesundheitsrisikos durch die Quecksilberverwendung im handwerklichen Kleingoldbergbau. Fünf in Peer-Review-Verfahren begutachtete wissenschaftliche Veröffentlichungen werden im Rahmen der vorliegenden Synopse zur Beantwortung der Forschungsfragen verwendet.

Materialien und Methoden: Die Dissertation umfasst die Verwendung unterschiedlicher Materialien und Methoden. Durch die Anwendung von narrativen und systematischen Reviews wurde Literatur einbezogen (Veröffentlichungen V1, V2, V3, V4 und V5). V1 ist ein narratives Review zu Kindergesundheit und Quecksilberexposition. In V2 und V3 wurde die Quecksilber-Körperlast durch Verwendung von Human Biomonitoring (HBM)-Daten erhoben in der Mongolei im Jahr 2008 (V2) und in Simbabwe in den Jahren 2004 und 2006 (V3) ausgewertet und mit den deutschen HBM Werten (HBM I und HBM II) verglichen (V2 und V3). Auf Quecksilber zurück zu führende Gesundheitseffekte wurden anhand von anamnestischen Daten, neuropsychologischen Testverfahren und klinischen Untersuchungen in der in Simbabwe erhobenen Stichprobe analysiert. Fälle von chronischen Quecksilbervergiftungen wurden identifiziert und die Stichprobenprävalenz bestimmt und für gesamt Simbabwe extrapoliert (V3). Das Summenmaß DALY (disability-adjusted life years) wurde unter Verwendung von primären, sekundären und modellierten Daten quantifiziert (V3). Eine erkrankungsspezifische und eine generische Gesundheitszustandsbeschreibung zur Vergiftung durch Quecksilber im Goldbergbau wurden entwickelt, welche für die Herleitung von Gewichtungsfaktoren (disability weight, DW) geeignet sind. Informationen zur gesundheitsbezogenen Lebensqualität (health-related quality of life, HRQoL) sowie eine umfassende Liste möglicher Symptome wurden durch Expertenbefragungen zusammengestellt. Die Auflistung von Symptomen wurde zudem durch eine systematische Literaturrecherche ergänzt (V4). Die Machbarkeit eines quecksilberfreien Goldgewinnungsverfahrens unter Verwendung von Borax wurde in einem Feldprojekt in Kadoma, Simbabwe, im Jahr 2013 getestet (V5).

Ergebnisse: Kinder reagieren besonders empfindlich auf Quecksilberexpositionen. Im handwerklichen Goldbergbau sind direkte und indirekte Belastungen denkbar, wobei unterschiedliche Personengruppen (Schwangere und stillende Frauen, im Goldbergbau involvierte Eltern, etc.) die Möglichkeit einer kindlichen Exposition beeinflussen können (V1). Daten einer Stichprobe von Frauen im gebärfähigem Alter, entweder involviert in die Goldgewinnung oder mit Wohnsitz in der Nähe von Goldminengebieten, aus den Verwaltungseinheiten Bornuur und Jar-galant in der Mongolei, wurden ausgewertet (V2). Eine weitere Stichprobe aus Simbabwe setzt sich aus männlichen und weiblichen Erwachsenen und Kindern involviert in die Goldgewinnung in Kadoma zusammen (V3). Beide Stichproben zeigen erhöhte Quecksilberkonzentrationen in Humanproben, sogar oberhalb von gesundheitsbezogenen Expositionsbegrenzungswerten (V2, V3). Die Auswertung von Gesundheitsdaten zeigt, dass möglicherweise durch Quecksilber verursachte Gesundheitseffekte bei Goldminenarbeiter/innen häufiger vorkommen als bei der Kontrollgruppe (V3). Die Krankheitslast von männlichen und weiblichen Erwachsenen und Kindern

involviert in die Goldgewinnung in Simbabwe im Jahr 2004 ist hoch (95.400 DALYs insgesamt, 8 DALYs/1.000 Personen). Eine Subgruppenanalyse identifizierte männliche Arbeiter, insbesondere im Kindes- und jungem Erwachsenenalter, als Personengruppe mit der höchsten Krankheitslast (V3). Die gesundheitsbezogene Lebensqualität von Fällen mit chronischer Vergiftung durch metallischen Quecksilberdampf kann erheblich durch ein breites Spektrum an Symptomen mit unterschiedlicher Symptomstärke beeinträchtigt sein (V4). Die Anwendung einer quecksilberfreien Goldgewinnungsmethodik unter Verwendung von Borax wurde anhand des Feldtests als machbar eingestuft, was eine Möglichkeit zur Reduktion des Gesundheitsrisikos durch Quecksilber im Goldbergbau sein kann (V5).

Diskussion: Die Dissertation trägt zu einem verbesserten Verständnis des Gesundheitsrisikos der Quecksilberverwendung im handwerklichen Goldbergbau bei. Das Gesundheitsrisiko durch im handwerklichen Kleingoldbergbau angewendetes Quecksilber kann als *erheblich, subgruppenspezifisch* und – tatsächlich – *reduzierbar* beschrieben werden. Das Gesundheitsrisiko ist *erheblich*, wenn die folgenden Aspekte berücksichtigt werden: das besondere Risiko von Kindern (V1), die hohe Quecksilberkonzentration in Humanproben von Arbeitern/innen und nicht im Goldbergbau involvierten Anwohnern/innen in Goldminengebieten (V2, V3), die hohe Prävalenz und die hohe Krankheitslast von Minenarbeitern/innen (V3), das breite Spektrum an möglichen Symptomen sowie die Beeinträchtigung der gesundheitsbezogenen Lebensqualität durch Quecksilbervergiftungen (V4). Das Gesundheitsrisiko ist *subgruppenspezifisch*, wenn das besondere Risiko von Kindern und die Relevanz des Verhaltens von anderen Personengruppen für die kindliche Exposition (V1), die hohe – nach Alter und Geschlecht variierende – Quecksilberkonzentration in Humanproben von Arbeitern/innen und nicht im Goldbergbau involvierten Anwohnern/innen in Goldminengebieten (V2, V3), die hohe – nach Alter und Geschlecht variierende – Prävalenz und Krankheitslast von Minenarbeitern/innen (V3) und das breite Spektrum an möglichen Symptomen, die bei Individuen als Folge von Quecksilberexpositionen auftreten können jedoch nicht müssen (V3, V4), berücksichtigt werden. Das Gesundheitsrisiko ist *reduzierbar*, wenn die erfolgreiche Testung einer quecksilberfreien Goldgewinnungsmethodik unter Verwendung von Borax berücksichtigt wird (V5). Im Vergleich zu internationaler Literatur sind große Unterschiede bezüglich der Quecksilberkonzentration in Humanproben beobachtbar. Die Kombination von HBM- und Gesundheitsdaten erscheint sinnvoll bei der Identifikation von Quecksilbervergiftungsfällen, was auch in Stichproben von Goldbergbauarbeitern/innen in anderen Ländern angewendet wurde. Die chronische Quecksilbervergiftung – verursacht durch die Exposition im Goldbergbau – wurde anhand der vorläufigen DALY-Schätzung unter die 20 höchsten Ursachen von Krankheitslast in Simbabwe im Jahr 2004, wie diese im Rahmen der

Global Burden of Disease Studie des Jahres 2004 von der Weltgesundheitsorganisation geschätzt wurde, eingeordnet. Dieses ist bislang die einzige nationale Schätzung der Krankheitslast durch die Quecksilberverwendung im handwerklichen Kleingoldbergbau. Andere Krankheitslastschätzungen für Quecksilber sind verfügbar, wobei der Forschungsbedarf für den Themenbereich handwerklicher Kleingoldbergbau (wie z.B. fehlende DWs) in der Literatur benannt ist. Die Ergebnisse der HRQoL der chronischen Vergiftung durch metallischen Quecksilberdampf ermöglichen Vergleiche der HRQoL mit anderen Gesundheitszuständen aus anderen Studien. Der quecksilberfreie Goldgewinnungsprozess unter Anwendung von Borax wurde erfolgreich in Kadoma, Simbabwe, so wie zuvor in anderen Ländern erprobt. Allerdings sind weitere Schritte für eine nachhaltige Einführung der Methodik notwendig. Darüber hinaus sind die begrenzten Literaturrecherchestrategien, kleine Fallzahlen und das Einbeziehen von Annahmen und modellierten Daten die Hauptlimitationen dieser Dissertation. Die Ergebnisse der Dissertation können in 8 von 9 Schritten einer Gesundheitsrisikoanalyse (human health risk analysis) eingeordnet werden. Die verwendeten Maßnahmen zur Beschreibung des Risikos sollten im Rahmen von gesundheitlichen Folgenabschätzungen (health impact assessment, HIA) zur Erfolgsüberwachung bei umfassenden Einführungen von quecksilberfreien Goldgewinnungsverfahren angewendet werden.

Schlussfolgerungen: Die Hauptschlussfolgerung der Dissertation lautet, dass das Gesundheitsrisiko durch die Quecksilberverwendung im handwerklichen Kleingoldbergbau *erheblich, subgruppenspezifisch* und *reduzierbar* ist. Unterschiedliche Materialien und Methoden wurden verwendet, wobei einige Methoden nie zuvor im Rahmen des Themas angewendet wurden (z.B. die Schätzung von DALYs und die Herleitung der HRQoL). Die Dissertation hat die Relevanz von unterschiedlichen Personengruppen bei der Beschreibung und Reduktion des Risikos durch Quecksilberverwendung im Goldbergbau identifiziert. Einige Subgruppen verlangen eine hohe Aufmerksamkeit entweder durch eine besonders hohe Vulnerabilität (Föten und Kinder), durch einen hohen Einfluss anderer Personengruppe (z.B. schwangere Frauen) auf ihre Exposition oder durch ihre besonders hohe Krankheitslast (junge männliche Goldminenarbeiter). Die Dissertation unterstreicht die Notwendigkeit gegen die anhaltende Bedrohung der Gesundheit durch die Quecksilberverwendung im handwerklichen Kleingoldbergbau anzukämpfen. Die Ergebnisse der Dissertation sollten als Impuls verstanden werden um Lösungen zu finden, die die Gesundheitsbedrohung durch die Verwendung von Quecksilber im handwerklichen Kleingoldbergbau reduzieren.

1 Background

Elemental mercury is used in artisanal small-scale gold mining (ASGM) today as it has been for the past 2,700 years, when amalgamation was first described as a common technology in gold mining (De Lacerda and Salomons 1998). ASGM is done by small groups of workers (families or other small groups, hence *small-scale*) using rudimentary, low-tech methods and a minimum of mechanization (hence *artisanal*) to mine gold (Hentschel et al. 2002, Hilson 2002). Safety equipment is not commonly used (Kessler 2013). Mercury is added to the crushed ore and amalgamates containing gold. The amalgam is then smelted and the mercury vaporized, leaving gold (UNEP 2012).

The main route of exposure to mercury in ASGM is inhalation of mercury vapor from amalgam smelting (UNEP and WHO 2008). However, exposure to other forms of mercury (e.g., methylmercury) and different paths of absorption (e.g., eating contaminated fish) cannot be excluded for miners. During mining, mercury is dumped in the environment, increasing the concentration in the atmosphere and international water bodies, where it is converted to methylmercury. Methylated mercury thus affects humans through food (especially fish) and water (UNEP 2013a). Hence, in addition to the local threat, the mercury thus released is also a global concern because of its high transportability, its persistence and its bioaccumulation in the environment (UNEP 2013b).

Why, then, do gold miners still use this well-known toxic pollutant? This is because using mercury makes the mining process simple, fast, inexpensive, and effective (Telmer and Veiga 2009). Gold mining is mostly poverty-driven and for many people it might be the only way to secure their livelihood (ILO 1999). Either they are not aware of the risks associated with it, or they have no choice and no access to alternative mining procedures (UNEP 2012).

The use of mercury in ASGM is described as “outsized threat to human health”¹ (Pure Earth and Green Cross Switzerland 2015, p. 5). The extent of this public health issue becomes obvious when considering that it is used in more than 70 countries (Telmer and Veiga 2009, UNEP 2012). An estimated 16 million artisanal small-scale gold (ASG) miners extract up to 450 tons of gold every year amounting to some 20% of the official global gold production (Seccatore et al. 2014). ASGM is recognized as the main anthropogenic source of global mer-

¹ Direct quotations are marked by double quotation marks (“...”) and indication of the page number.

cury emissions into air, here assuming an emission of more than 700 tons per year – 37% of all anthropogenic mercury emissions (UNEP 2013a).

At the country level several measures like mercury consumption, emissions into air, emission in air per capita, or the ratio of mercury consumed to gold produced (Hg:Au ratio) are reported to identify hot spots of mercury pollution from ASGM. China was identified as the country with the highest mercury consumption in ASGM with a mean of 450 tons per annum (t/a) estimated for 2008. Aside from China, the top 10 consumers of mercury in ASGM are Indonesia (145 t/a), Colombia (75 t/a), Brazil (45 t/a), Peru (30 t/a), the Philippines (25 t/a), Zimbabwe (25 t/a), Ecuador (15 t/a), Guyana (15 t/a), Venezuela (15 t/a), and Mongolia (12 t/a) (Telmer and Veiga 2009). Colombia was identified as the world's worst mercury polluter per capita due to gold mining (Cordy et al. 2011). The Hg:Au ratio is assumed to be excessively high, with a ratio of 70:1 in Burkina Faso. Summarized by continent, the highest ratio is assumed to be in Africa (average Hg:Au ratio: 8.5) compared to Asia (average Hg:Au ratio: 3.3) and South America (average Hg:Au ratio: 2.0). The most inefficient ASGM worldwide is therefore found in Africa. Consumption of mercury is highest in countries with the lowest technology (Seccatore et al. 2014).

While on the one hand, high-income countries already have identified and controlled their worst environmental pollution problems (e.g., banning asbestos), the populations in poorer countries are increasingly exposed to environmental pollutions released during industrial processes (Landrigan and Fuller 2015). An example of such an environmental pollution problem in poor countries is the use of mercury in gold mining, because of the enormous quantities of mercury released (Landrigan and Fuller 2015). The work is performed under unsafe conditions and mostly outside the supervision of regulating systems regarding prevention, reporting, and compensation for occupational diseases (ILO 2013, Landrigan and Fuller 2015). Often, ASGM activities are informal or even illegal (Hentschel et al. 2002, Hilson 2002). As a consequence, health effects are mainly undetected and unreported and the associated burden is not recognized (ILO 2013).

So far, not enough attention has been given to the impact of mercury on population health (Prüss-Üstun et al. 2011) and particularly to the use of mercury in ASGM (Pure Earth and Green Cross Switzerland 2015). Describing environmental risks through risk assessments like disability-adjusted life years (DALYs) are important for predicting, comparing, and managing the issue and to build the basis for prevention. Until now, no sustainable economic solution has been found to eliminate mercury emission in gold mining (Zolnikov 2012).

The human health risk from the use of mercury in ASGM urgently needs to be described and reduced, as made concrete in the 2013 Minamata Convention on Mercury. This convention was intended to be a “global legally binding instrument” aiming on protecting human health and the environment against mercury (UNEP 2013b, p. 3). According to the official website², 128 countries have signed and 25 ratified the convention. As previously mentioned, the 11 countries consuming the most mercury in ASGM have signed and of these, Guyana, Mongolia, and Peru already ratified the Convention. The Convention will come into force 90 days after the ratification by the 50th country. ASGM is explicitly regulated in Article 7 and Annex C calling for “steps to reduce, and where feasible eliminate” the use and emission of mercury in mining (UNEP 2013b, p. 17).

The use of mercury in ASGM is an enduring public health issue. However, the signatures on the Minamata Convention on Mercury might indicate a global recognition of the issue. This thesis applies public health measures to describe and reduce the burden of mercury used in ASGM, as called for by the Minamata Convention on Mercury. Five peer-reviewed research papers (P) form the basis of this thesis (see p. v). These include two overarching papers without national connections (P1, P4) as well as three papers directly related to ASGM in Mongolia (P2) and Zimbabwe (P3, P5), two of the top 11 mercury polluters in ASGM. In Chapter 2, the current state of research is described to reveal research gaps and to derive relevant objectives and research questions treated by this thesis (Chapter 3). Chapter 4 comprises a description of the materials and methods used in the five papers this thesis is based on. The results are summarized in Chapter 5. This thesis ends with an overall discussion (Chapter 6) and conclusions (Chapter 7).

2 Current state of research

The toxicity of mercury has been studied extensively. Mercury exists in elemental, inorganic, and organic forms, each with different toxic effects and causes a wide range of acute and chronic health effects (ATSDR 1999, Guzzi and La Porta 2008). The nervous system and kidneys are particularly sensitive to this element. The harmful effects on the development of unborn children and infants are especially alarming (ATSDR 1999).

Several sources of mercury emissions are ubiquitous, exposing humans and threatening human health. About 10% of all mercury emissions are assumed to occur through natural emis-

² UNEP: Minamata Convention on Mercury [Website]. Access: <http://www.mercuryconvention.org/> [last access April 12, 2016].

sions which cause background concentrations in the environment. Mercury is naturally released due to weathering of rocks containing mercury, volcanic eruption, or other geothermal activity. Re-emissions and re-mobilization of previously deposited (originally natural or anthropogenic released) mercury is the source of around 60% of all mercury emissions. The remaining 30% are emitted from anthropogenic sources. The main anthropogenic source is intentional use of mercury in ASGM (UNEP 2013a).

Health and human biomonitoring (HBM) studies in several countries investigated human exposure and the health effects resulting from the use of mercury in ASGM. Recently, two reviews were published which summarize ASGM studies showing mercury concentrations in blood, hair (Gibb and O'Leary 2014), and urine (Gibb and O'Leary 2014, Kristensen et al. 2014). Gibb and O'Leary (2014) found more than 60 studies reporting analyzes of biomarkers of exposure to mercury in gold mining communities in 19 countries. Kristensen et al. (2014) limited the focus to urine samples and summarized 26 studies from 14 countries. Since the publication of these reviews, another 10 papers reporting results for 7 countries have been published (Castilhos et al. 2015, Faial et al. 2015, Marinho et al. 2014, Mostafazadeh et al. 2013, Niane et al. 2015, Olivero-Verbel et al. 2015, Peplow and Augustine 2014, Rajaei et al. 2015a, Sanchez Rodriguez et al. 2015, Suvd et al. 2015) as well as another review focusing on Ghana (Basu et al. 2015).

All in all, published HBM data for ASGM communities in more than 20 countries was found. When considering the 11 countries consuming the most mercury in ASGM (Telmer and Veiga 2009) as described in Chapter 1, no HBM data for the exposure to mercury of ASG miners in Guyana was found. HBM data published on gold miners in Mongolia (Baeuml et al. 2011, Boese-O'Reilly et al. 2012a, Boese-O'Reilly et al. 2012b, Steckling et al. 2011) and Zimbabwe (Baeuml et al. 2011, Bose-O'Reilly et al. 2004, Bose-O'Reilly et al. 2008a, Steckling et al. 2014a) were those taken from the projects which formed part of this thesis. This data was analyzed in several contexts. Recently, the sample in Mongolia has been reanalyzed (Suvd et al. 2015).

Besides the HBM publications reviewed by Gibb and O'Leary (2014) as described above, the same review focused on mercury-related health effects of ASGM communities. 17 publications referring to 10 countries were identified. The effects described include neurological and kidney effects, and (auto)immune toxicity. Kristensen et al. (2014) reviewed health effects when described in the above mentioned HBM studies and found 12 papers focusing on eight countries. They listed mercury-related health symptoms such as movement disorders, impaired short-term memory, gingivitis, and proteinuria. Another six studies, each focusing on

another country and investigating different health outcomes, were published after the above mentioned reviews (Motts et al. 2014, Peplow and Augustine 2014, Rajaei et al. 2015b, Sanchez Rodriguez et al. 2015, Saunders et al. 2013, Suvd et al. 2015). Basu et al. (2015) reviewed national data on human health effects from the use of mercury for Ghana.

Considering again the 11 countries with the highest mercury consumption in ASGM, there seem to be no publications about mercury-related health effects in gold miners from Guyana and Mongolia. For Zimbabwe, there are no health data published except those from the projects which make up this thesis (Bose-O'Reilly et al. 2004, Bose-O'Reilly et al. 2008a, Steckling et al. 2014a). This data was analyzed in several contexts.

While several investigations worldwide have focused on determining the human body burden and health effects attributable to the use of mercury in ASGM, its impact on population health has been addressed far less often. The quantification of disability-adjusted life years (DALYs) is one way to determine population health. The DALY is the outcome of burden of disease (BoD) and environmental BoD (EBD) analyses. BoD and EBD can be used in public health to support policy decision-making where several aspects of disease are combined. It is possible to compare risk factors, diseases, years, and populations and to monitor public health issues. EBD is the environmental component of BoD and quantifies the disease burden which can be attributable to environmental risk factors (Prüss-Üstun et al. 2003).

There is a wide range of studies quantifying the burden of (environmental) risk factors (Hornberg et al. 2014). Following the criteria for inclusion, 42 EBD studies on biological, chemical, and physical stressors were found, including 15 EBD studies focusing on metals. Another review summarized 12 BoD studies on lifestyle factors (e.g., smoking), physiological states (e.g., high blood pressure), or societal conditions (e.g., occupational exposure) (Polinder et al. 2012). The comparative risk assessment (CRA) of the Global Burden of Disease (GBD) study might be the most extensive investigation quantifying the DALYs of 79 risk factors (Forouzanfar et al. 2015). Another important source is the EBD series of the World Health Organization (WHO) which gives practical guidance for national and local estimates and presents its own quantifications for selected risk factors (WHO 2015). Although much has been done, many public health risks arising from risk factors have not been considered yet. Landrigan and Fuller (2015, p. 762) call it an “undercounting of the effects of pollution in estimations of the Global Burden of Disease” (Landrigan and Fuller 2015, p. 762). Missing information on the health (and economic) impact might be a reason why environmental pollutions has been widely overlooked and is neglected by international development agendas (Landrigan and Fuller 2015). Determining the BoD of (risk factor associated) health

effects with limited data is particularly important to raise awareness in policy makers and avoid an implicit assumption that these causes have no burden (Mathers 2008).

Prüss-Üstun et al. (2011) reviewed studies on the global burden of chemicals resulting in an attributable burden of nearly 6% of the estimated total global burden, while chemicals which had not been quantified, such as mercury, led to an underestimation. While the global burden of mercury has not been quantified yet, some DALY quantifications of communities exposed to mercury are available. Chatham-Stephens et al. (2013) quantified the burden of renal toxicity from exposure to inorganic mercury at toxic waste sites including but not limited to artisanal gold mining in India, Indonesia, and the Philippines. Poulin and Gibb (2008) quantified the burden of mild mental retardation (MMR) due to exposure to methylmercury in different subgroups, including some communities living near gold mining areas. While not included, determining the burden from exposure to elemental mercury used in ASGM was identified as a critical research need (Poulin and Gibb 2008).

Pure Earth (previously named Blacksmith Institute) identified the use of mercury in ASGM as the worst of the top 10 toxic pollution problems in 2011, measured using the estimated number of people at risk. The intention was to quantify the global health burden of mercury in ASGM expressed in DALYs based on these findings. This, however, failed because the data needed to quantify DALYs was lacking. One factor was the missing disability weight (DW) necessary for BoD analyses (Harris and McCartor 2011). In the most recent report update (Pure Earth and Green Cross Switzerland 2015), the missing DW for BoD analyses of health effects from elemental mercury again prohibited DALY quantification. In order to fill this gap, Pure Earth is collaborating with a German research team to derive the necessary DW for mercury intoxication³ (Pure Earth and Green Cross Switzerland 2015).

A DW describes the severity of health states on a scale from zero (health state without disability) to one (health state comparable to death) and is a factor in the morbidity part of DALY quantifications. The DW adjusts the time lived in a specific health state and can thus be compared and combined with the time lost due to premature mortality (Murray 1994). Several initiatives aimed at deriving DWs for a variety of health states (Haagsma et al. 2014) and 235 DWs were derived in the largest DW study to date (Salomon et al. 2015). However, specific conditions like chronic intoxication from exposure to mercury in ASGM were not considered. When deriving DWs for BoD analyses, several methods can be used, such as the valuation

³ This refers to the second part of the project DiWIntox (Disability Weights for chronic mercury intoxication) awarded to the University Hospital Munich in collaboration with Bielefeld University and the Germany Environment Agency, funded by Pure Earth. The first part of the project has been published and is included in this thesis as Paper 4 (Steckling et al. 2015).

method or the composition of the panel asked to assess the health states (Haagsma et al. 2014, Tobollik et al. 2016). Although there are several ways to derive DWs, they all rely heavily on descriptions of health states. Recommended are health state descriptions combining disease-specific and generic information (Haagsma et al. 2014). Information about the health-related quality of life (HRQoL) as a generic description is already applied in some studies (Haagsma et al. 2008a, Haagsma et al. 2008b, Kruijshaar et al. 2005, Schwarzinger et al. 2003, Stouthard et al. 2000, Stouthard et al. 1997, van Spijker et al. 2011). Besides the missing DW for mercury-related health states in ASGM, there is also no information about their HRQoL available.

Although there is a growing public health awareness of the importance of mercury in ASGM, no comprehensive and comparative assessment of the impact on population health is available. The missing DW allows no DALY quantification and data on its HRQoL is likewise missing.

In addition to the research on describing the health risk of mercury in ASGM, attempts are being made to reduce the health risk. Several options are available (e.g., education programs, awareness campaigns, strategies to reduce the mercury consumption or even to stop the use of mercury) but no single solution has been found which could be generally applicable in ASGM (UNEP 2012, Zolnikov 2012). Simply banning mercury is unrealistic and without appropriate mercury-free mining methods the miners would lose their livelihoods (Schmidt 2012). One promising way to reduce the mercury burden from gold mining is applying borax for a mercury-free direct smelting process (Styles et al. 2010, UNEP 2012).

The boron compound borax, also named sodium tetraborate ($B_4Na_2O_7 \cdot 10H_2O$), is a combination of naturally occurring mineral boron and oxygen. Such compounds are named borates. Borax is used in many products like soap, creams, and pesticides. Inhalation of borates like borax is associated with mild irritation of the eyes, throat and nose. Boron and borax are not thought to cause cancer; however, ingesting large amounts can be fatal. Animal studies showed that exposure to large quantities of boron or its compounds can be related to reproductive toxicity (ATSDR 2010), which is why it is on the list of substances of very high concern (ECHA 2010). However, reproductive toxicity has not been confirmed for humans. Epidemiological studies of Chinese workers in borax mines, for example, showed no negative effects on humans from exposure to borax (ATSDR 2010, Basaran et al. 2012, Duydu et al. 2012a, Duydu et al. 2011, 2012b, Riederer and Caravanos 2013, Robbins et al. 2010, Scialli et al. 2010). A toxic concentration of boron or compounds is “by far not reachable for humans under conditions of normal handling and use” (Duydu et al. 2011, p. 589). The exposure of gold miners using borax to extract gold is distinctly lower than that of boron miners and even

they show no adverse effects. It was concluded that there is no elevated risk to reproductive or other health effects for miners using borax and that the use of borax in gold mining is by far less toxic than the traditional amalgamation process (Koster-Rasmussen et al. 2016, Riederer and Caravanos 2013).

Applying borax together with gravity methods has been used for decades to mine gold in the Benguet province of the Philippines (Appel and Jønsson 2010, Koster-Rasmussen et al. 2016). Over the last few years, this procedure was also successfully tested in Bolivia (Appel et al. 2015, Appel and Na-Oy 2014, Pure Earth 2016a), Colombia (Grinell 2014), Ghana (Amankwah et al. 2010, Styles et al. 2010), Mongolia (Pure Earth 2016b), Nicaragua (Grinell 2014), Sumbawa in Indonesia (Blacksmith Institute 2013), the Philippines (Koster-Rasmussen et al. 2016, Perez et al. 2007), and Tanzania (AGENDA 2010, Appel and Jønsson 2010, Appel and Na-Oy 2013). In Kalimantan in Indonesia the method failed because of the consistency of the ore (Barber 2012), although a further initiative to test the procedure at 50 mining sites in Kalimantan has started since then (Pure Earth and Green Cross Switzerland 2015). Besides several positive reports about using borax in gold mining, the specific conditions in which borax might be useful have to be considered (Veiga 2011, Veiga et al. 2014).

While successful testings in several countries have been reported, it might be reasonable to test the mercury-free gold extraction process using borax in further ASGM regions. With regard to the literature found, it seems that there are no publications indicating that the procedure has been tested in Brazil, China, Ecuador, Guyana, Peru, Venezuela, or Zimbabwe, when again considering the top 11 mercury consumers in ASGM as identified by Telmer and Veiga (2009).

In conclusion, the state of research for describing and reducing the health risk from mercury used in ASGM is characterized by the existence of HBM and health data for one or more samples in most of the 11 countries with the highest mercury consumption in ASGM. Less attention has been given to Guyana, Mongolia, and Zimbabwe, as evident from the current reviews (Gibb and O'Leary 2014, Kristensen et al. 2014) supplemented by a PubMed⁴ search of new literature published between December 2012 and January 2016⁵. However, the samples from Mongolia and Zimbabwe analyzed in this thesis were also analyzed in other con-

⁴ “PubMed comprises more than 25 million citations for biomedical literature from MEDLINE, life science journals, and online books” (<http://www.ncbi.nlm.nih.gov/pubmed>; last access April 12, 2016).

⁵ The following search terms were applied in PubMed (<http://www.ncbi.nlm.nih.gov/pubmed>; last access April 12, 2016) to find new publications not included in the recent reviews (Gibb and O'Leary 2014, Kristensen et al. 2014): The terms *gold mining mercury* were combined with *biomonitoring, blood, hair, health, and urine* [limitation: published between 2012/12/01 and 2016/01/31].

texts before or after these thesis papers were published. There are currently few initiatives which aim at determining the population health risk from the use of mercury in ASGM, however, data scarcity (esp. a missing DW) has not allowed quantifications in DALYs. The mercury-free gold extraction procedure using borax was successfully tested in some countries. It has also been tested recently in Mongolia (Pure Earth 2016b), although there were no tests in several of the 11 main countries in which mercury is consumed in ASGM (e.g., Zimbabwe).

3 Objectives and research questions

The overall objective of this thesis is to apply public health measures to describe the health risk due to the use of mercury in ASGM and to test a mercury-free extraction procedure to reduce the risk. This thesis therefore contributes to answering the general research question:

➤ **How to describe and reduce the human health risk of mercury used in ASGM?**

This research question yielded five scientific papers published in peer-reviewed journals. Table 1 gives an overview of the specific objectives and research questions of these five papers. The central question of this thesis – *describing* and *reducing* the human health risk from mercury used in ASGM – was subdivided and specified in the following subquestions (I to IV) and objectives (a to p). Subquestion I focuses on *subgroups* relevant for ASGM and thus contributes to both *describing* and *reducing* the risk (papers P1, P2, P3, P4, P5). Subquestions II (*mercury body burden*; P2, P3) and III (*health burden due to mercury*; P1, P3, P4) contribute to the part of the central question *describing the risk*, subquestion IV (P5) contributes to the aspect *reducing the risk*.

Table 1: Summary of the objectives, subgroups, and research questions of the five papers forming the basis of this thesis

Paper (P)	Objective	Subgroup	Research questions
P1: Bose-O'Reilly et al. (2010c)	Give an extensive review of exposure to mercury and children's health.	Children	What is known about exposure to mercury and children's health?
P2: Steckling et al. (2011)	Determine the mercury body burden of female gold miners and not occupationally exposed residents in gold mining areas in Mongolia.	Female miners, residents not involved in mining but living in mining areas, and controls of child-bearing age in Mongolia	What is the mercury body burden of female gold miners in Mongolia determined from blood, urine, and hair samples?
P3: Steckling et al. (2014a)	Check data availability and derive a preliminary estimate of DALYs due to mercury use in ASGM in Zimbabwe in 2004.	Male and female gold miners and controls in several age groups in Zimbabwe	What is the mercury body burden of gold miners in Zimbabwe determined from blood, urine, and hair samples? What is the sample prevalence of chronic mercury intoxication in a subsample of gold miners and extrapolated to all of Zimbabwe? How many DALYs are attributable to the use of mercury in ASGM in Zimbabwe in 2004? What are the research needs to improve DALY estimation?
P4: Steckling et al. (2015)	Develop disease profiles of intoxications from exposure to mercury in gold mining by including the HRQoL to improve the data basis for EBD analyses of gold miners exposed to mercury.	Adult gold miners with mercury intoxication	How can the health outcome of ASG miners exposed to mercury be labelled? How can the health outcome of interest be differentiated in disease stages? What is the characteristic exposure situation of ASG miners using mercury? Which health symptoms are common for the health outcome of interest? What is the HRQoL of individuals showing the health outcome of interest?
P5: Steckling et al. (2014b)	Test local conditions introducing a mercury-free gold mining technology entailing the use of borax in a field project in Kadoma, Zimbabwe.	Male and female gold miners, local officials from agencies and ministries in Zimbabwe	Is the ore in Kadoma, Zimbabwe, suitable for extracting gold using borax? Are the equipment and materials necessary for the borax method available in Kadoma, Zimbabwe? Are the miners interested in using borax?
Abbreviations: ASG: artisanal small-scale gold; ASGM: artisanal small-scale gold mining; EBD: environmental burden of disease; DALY: disability-adjusted life year; HRQoL: health-related quality of life; P1 to P5: papers this thesis is based on			

1. Which are relevant subgroups when aiming for describing and reducing the human health risk from mercury used in ASGM?

The objective is to investigate relevant subgroups in ASGM when aiming at describing and reducing their mercury burden. The considered subgroups of interest are:

- a) children [P1],
- b) female gold miners and residents not involved in mining but living in mining areas of child-bearing age in Mongolia, [P2],
- c) male and female adult and child miners, in Zimbabwe [P3],
- d) adult miners with mercury intoxication [P4], and
- e) miners and other local parties involved in ASGM in Zimbabwe [P5].

II. What is the mercury body burden in ASGM areas?

The objective is to examine the mercury body burden determined by mercury concentrations in blood, hair, and urine samples from:

- f) female gold miners and residents not involved in mining but living in mining areas of child-bearing age in Mongolia [P2] and
- g) miners in Zimbabwe [P3] and
- h) to compare the mercury concentrations with the German HBM values (HBM I and II) [P2, P3].

III. What is the health burden from exposure to mercury used in ASGM?

The objective is to describe the mercury health burden by:

- i) summarizing available data on exposure to mercury and children's health in ASGM [P1],
- j) determining the sample prevalence of chronic mercury intoxication and exposure distribution as well as extrapolating the population prevalence of gold miners in Zimbabwe [P3],
- k) reviewing the availability of health and exposure data and estimating preliminary DALYs attributable to the use of mercury in ASGM in Zimbabwe [P3],
- l) determining the HRQoL of gold miners intoxicated by mercury [P4], and
- m) improving the data basis for DALY estimates attributable to the use of mercury in ASGM by developing disease profiles including disease-specific and generic descriptions which can be used to derive DW [P4].

IV. How can the health risk from the use of mercury in ASGM be reduced?

The objectives are:

- n) to determine if equipment and materials necessary for the mercury-free gold extraction procedure using borax are available in Kadoma, Zimbabwe [P5],
- o) to determine if the local parties involved (gold miners, ministries, agencies) in Kadoma, Zimbabwe, are interested in a mercury-free gold extraction procedure [P5], and
- p) to test if the mercury-free gold extraction procedure using borax is suitable for extracting gold from the ore in Kadoma, Zimbabwe [P5].

4 Materials and methods

This thesis comprises different materials and methods (Table 2), as summarized in the subsequent chapters titled according to the main methods applied: literature review (Chapter 4.1), statistical and epidemiological data analyses (Chapter 4.2), EBD (Chapter 4.3), expert elicitation and HRQoL (Chapter 4.4), and practical testing of a mercury-free gold extraction procedure (Chapter 4.5). Further details on the materials and methods are described in the articles themselves.

Table 2: Summary of the materials and methods used for the five papers forming the basis of this thesis

Paper (P)	Materials	Methods
P1: Bose-O'Reilly et al. (2010c)	International literature (incl. grey literature)	<i>Data collection:</i> Narrative literature review <i>Data analysis:</i> Synthesize the data collected
P2: Steckling et al. (2011)	Data about HBM, socioeconomic factors, and possible confounder	<i>Data collection:</i> Field project in Mongolia in 2008 ¹ <i>Data analysis:</i> Descriptive statistics; comparison with threshold values, box-plots; inferential statistics (Kruskal-Wallis test, Mann-Whitney U test, Chi-square test, likelihood ratio)
P3: Steckling et al. (2014a)	International literature (incl. grey literature); data about HBM, health, socioeconomic factors, and possible confounder	<i>Data collection:</i> Field project in Zimbabwe in 2004 and 2006 ¹ ; systematic literature review <i>Data analysis:</i> Descriptive statistics: comparison with threshold values; inferential statistics (Chi-square test); combining HBM and health data and diagnosing cases of chronic mercury intoxication; EBD (disease modeling using DisMod II, estimation of DALYs, analyses of competing scenarios)
P4: Steckling et al. (2015)	International literature (incl. grey literature); transcript of expert interview; presentation by one expert	<i>Data collection:</i> Expert group interview with open discussions; guiding questionnaire including the EuroQol questionnaire (EQ-5D+C-3L); systematic review of the literature <i>Data analysis:</i> Synthesize the data collected; develop disease profiles
P5: Steckling et al. (2014b)	Documentations from field project (notes, pictures, videos)	<i>Data collection:</i> Field project in Zimbabwe in 2013 including theoretical workshop and practical testing; trial and error; observations and discussions <i>Data analysis:</i> Synthesize the data collected
<p>Abbreviations: DALYs: disability-adjusted life years; DisMod II: disease model, second version, developed by the WHO; EBD: environmental burden of disease; EQ-5D+C-3L: EuroQol questionnaire with 5 dimensions (mobility, self-care, usual activities, pain/discomfort, anxiety/depression) accompanied by the cognition add-on questionnaire, coded on 3 levels for responses (1: no problems; 2: problems; 3: severe problems); HBM: human biomonitoring</p> <p>Further explanations: ¹ The doctoral candidate was involved in the collection of all data except in the field projects in Mongolia (2008) and Zimbabwe (2004, 2006), where the primary data were made available for her to analyze.</p>		

4.1 Literature review

The fundamental basis for every paper in this thesis was existing knowledge. Aspects of narrative and systematic reviews were applied to detect the information of interest.

P1 is a narrative review which aimed at describing exposure to mercury and children's health. A narrative review receives less attention than a systematic literature review with a documented search strategy. Also, narrative reviews might be biased by the authors' decisions (Pae 2015). However, the advantage of this kind of review is that it can discuss a broad range of issues and thus give a comprehensive overview (Callcut and Branson 2009, Cook et al. 1997).

There is no specific, but rather a broad research question and the selection and appraisal of literature as well as the sources included are not usually described (Callcut and Branson 2009). P1 includes an overview of several topics relevant to children's exposure to mercury. In addition to data on children's exposure to mercury used in ASGM, the paper also includes information beyond the scope of this thesis (e.g., children's exposure to mercury as part of religious rituals). The content of the paper was defined during WHO workshops in Bonn and Geneva in 2007. The paper comprises condensed information while a comprehensive report also exists as a result of the WHO meetings (WHO 2010a) mentioned above.

P2, P3, P4, and P5 used aspects of narrative reviews to outline the state of research and integrate the results into previous research. The literature review was particularly relevant for the project described in P5, where a mercury-free gold extraction method was tested in Zimbabwe. The tests used a mining procedure applied earlier in other countries. While the participation of international experts was hampered by a limited time frame, tests were based on published descriptions of the procedure supplemented by (unpublished) written and audio-visual information provided upon request by experts in gold extraction.

Systematic strategies to review the literature were necessary for P3 and P4. Systematic reviews are useful if the evidence on a specific topic needs to be summarized to answer a specific research question. The literature search follows a predefined strategy and uses various sources. The specific research question guides specific data extraction (Pae 2015). The preliminary DALY estimation for chronic mercury intoxication in ASGM in Zimbabwe (P3) was based on a comprehensive search of secondary data (e.g., distribution of ASGM in Zimbabwe, case fatality and remission of chronic mercury intoxication). P4 comprises a systematic literature search to identify symptoms caused by exposure to mercury used in gold mining as well as symptom severity and probability of occurrence used for the disease-specific parts of the disease profiles. For both papers, data sources were publications listed in PubMed and reports by international organizations involved in ASGM research. Selected search terms were defined and literature was screened to find necessary information.

4.2 Statistical and epidemiological data analyses

Primary data from field projects were statistically and epidemiologically analyzed. The data was taken from cross-sectional projects in Mongolia (P2) and Zimbabwe (P3). The projects were conducted in gold mining regions of the districts Bornuur and Jargalant in Mongolia and Kadoma in Zimbabwe. Control groups were surveyed in Khushaat district, Mongolia, and Chikwaka, Zimbabwe, which are regions without any gold mining. The project in Mongolia

was conducted by the WHO in Ulaanbaatar and Geneva, the Mongolian Ministry of Health (MoH), and the Austrian Private University of Health Sciences, Medical Informatics and Technology (UMIT) in September 2008 (P2). Data from 2 projects in Zimbabwe were used. The first data collection, in 2004, was part of the Global Mercury Project (GMP), conducted by the United Nations Industrial Development Organization (UNIDO) with funding from the Global Environment Facility (GEF) (Bose-O'Reilly et al. 2004). The 2006 project in Zimbabwe was funded and conducted by the Ludwig-Maximilians-University Munich (LMU). Data from both projects in Zimbabwe was combined for this analysis to increase the sample size (P3). This was beneficial for the subsequent EBD analysis (see Chapter 4.3).

The projects included different subgroups. The Mongolian project focused on women of child-bearing age ($n= 198$). The project conducted in Zimbabwe in 2006 investigated women and their infants (number of mothers: $n= 203$), while the 2004 project included randomly selected male and female subjects ($n= 69$). The analysis used data of subjects involved in mining (P2, P3), living in mining areas without involvement in mining⁶ (P2), and control groups (P2, P3).

Data on socioeconomic and confounding factors, mercury in human specimens (P2, P3), and health (P3)⁷ were collected for the field projects. Socioeconomic and confounding factors were surveyed using a questionnaire. Blood (Mongolia 2008; Zimbabwe 2004), hair, and urine samples (Mongolia 2008; Zimbabwe 2004, 2006) were collected⁸. The stored samples were provided to laboratories and analyzed. Health data was surveyed with clinical examinations, neuropsychological tests, and with a questionnaire to compile anamnestic data.

Descriptive and inferential statistics were used for the data analyses. Frequencies, arithmetic mean, median, minimum, maximum, and 95th percentile were used if necessary to describe sociodemographic characteristics, potential confounders from subgroups, and mercury in blood ($\mu\text{g/l}$), urine ($\mu\text{g/l}$ and $\mu\text{g/g}$ creatinine), and hair ($\mu\text{g/g}$). Results of the HBM analyses were compared with the German HBM values (HBM I and HBM II) and classified as either below HBM I, between HBM I and HBM II, or above HBM II.⁹ These are “health-related biological exposure limit values” (Schulz et al. 2012, p. 150). By definition, a health hazard

⁶ Data on residents not involved in mining but living in mining areas also is available for Zimbabwe but not given in Paper 3. The reason was to reduce the complexity of the paper by focusing on miners rather than on residents without involvement in mining.

⁷ Health data also is available for Mongolia but not shown in Paper 2. The reason was the focus of the paper on HBM data.

⁸ Breast milk was also collected but analyzed in other contexts (Bose-O'Reilly et al. 2008b).

⁹ The data from Zimbabwe were additionally compared with the biological workplace tolerance level (BAT), see Table 3 and Steckling et al. (2014a).

cannot be ruled out if mercury concentration in human specimens falls between HBM I and HBM II. Concentrations above HBM II indicate an increased health risk (HBM Commission 1996, 2014). Frequencies of health effects by subgroup were shown and summarized in a medical score sum. The classification into HBM values and the medical score sum were combined to diagnose chronic mercury intoxication (see below).

Inferential statistics included Kruskal-Wallis-test, Mann-Whitney U-test, likelihood ratio (P2), and Chi-square-test (P2, P3). The data from Mongolia (P2) were analyzed in more detail because of the focus on HBM. Kruskal-Wallis and Mann-Whitney U-test for unpaired samples were used to find possible differences of the mercury concentration in human specimens of the three subgroups non-occupationally involved residents in mining areas, miners, and controls. The Kruskal-Wallis test was used to compare all three subgroups. The Mann-Whitney U-test compares the medians of each exposure group with the control group separately. The likelihood ratio and chi-square were used to compare the findings with threshold limits. The chi-square was used to analyze socioeconomic and confounder differences between miners (and residents not involved in mining but living in mining areas) and controls (P2, P3) as well as the presence of single health effects (P3).

For the sample from Zimbabwe, cases of chronic mercury intoxication were identified using a diagnostic algorithm (Drasch et al. 2001), explained in Table 3. Mercury values classified as below HBM I, between HBM I and HBM II, or above HBM II (compare row b in Table 3) were combined with health data (compare row a in Table 3) summarized in a medical score sum classified as low (0 to 4), medium (5 to 9), or high (10 to 21; compare row c in Table 3). This categorization was based on a previous study (Drasch et al. 2001) to ensure comparability of results, as was done with other analyses (Bose-O'Reilly et al. 2004, 2010a, 2010b, Pereira Filho et al. 2004). The diagnostic algorithm is based on the premise that the higher the mercury levels in the samples, the fewer symptoms are needed for a positive diagnosis of chronic mercury intoxication. Conversely, low mercury levels and many typical symptoms also reflect chronic mercury intoxication.

Table 3: Diagnostic algorithm for chronic mercury intoxication (adapted from Steckling et al. 2014a, p. 5, with data from Drasch et al. 2001)

[a] Diagnostic algorithm	Exposure limit values [b]	Medical score sum [c]: Low (0-4)	Medical score sum [c]: Medium (5-9)	Medical score sum [c]: High (10-21)
	Hg [#] <HBM I	no intoxication	no intoxication	no intoxication
Hg [~] >HBM I and <HBM II	no intoxication	no intoxication	no intoxication	intoxication
Hg [~] >HBM II and <BAT	no intoxication	intoxication	intoxication	intoxication
Hg [~] >BAT	intoxication	intoxication	intoxication	intoxication

[b] Exposure limit values* for mercury in HBM samples	Exposure limit values	Hg in blood (µg/l)	Hg in urine (µg/l)	Hg in urine (µg/g cr.)	Hg in hair (µg/g)
	<HBM I	0-<5	0-<7	0-<5	0-<1
>HBM I and <HBM II	5-<15	7-<25	5-<20	1-<5	
>HBM II and <BAT	≥15-<25	≥25-<30	≥20-<25	≥5	
>BAT	≥25	≥30	≥25	/	

[c] Indicators of the medical score sum ⁺	Anamnesis	Clinical examination	Neuropsychological tests
	Metallic taste (0/1)	Bluish coloring of the gingiva (0/1)	Frostig test ¹ (0/1/2)
Excessive salivation (0/1)	Ataxia of gait (0/1)	Matchbox test ² (0/1/2)	
Tremor at work (0/1)	Finger-to-nose tremor (0/1)	Memory test ³ (0/1/2)	
Sleeping problems at night (0/1)	Dysdiadochokinesia (0/1)	Pencil tapping test ⁴ (0/1/2)	
Health problems worsened since having been exposed to mercury (0/1)	Heel-to-knee ataxia (0/1)		
	Heel-to-knee tremor (0/1)		
	Mento-labialreflex (0/1)		
	Proteinuria (0/1)		

Abbreviations: BAT: biological workplace tolerance level (*Biologischer Arbeitsplatztoleranzwert*); cr.: creatinine; HBM I and II: human biomonitors values I and II from the HBM commission of the German Environment Agency; Hg: mercury

Explanations of numbers: ¹ Frostig test for examining tremor and visual-motor capacity: The test person must draw a straight line from one symbol to another across a narrow gap without touching the margins, staying into the areas or breaking the line. This is a subtest of a more detailed test by Lockowandt (1996). ² Matchbox test for examining coordination, intentional tremor and concentration: The subject must collect matches and put them in the matchbox as quickly as possible while alternating the hand used. The matchbox test is part of the motor proficiency test MOT (*Motoriktest*) developed by Zimmer and Volkamer (1984). ³ Memory test for short-term memory: The test subject must repeat numbers shown in columns in the correct order (Masur 2000). ⁴ Pencil tapping test for examining intentional tremor and coordination: The test subject must make as many dots as possible in 10 seconds by repeatedly tapping a pencil on a piece of paper. This test is also part of MOT (Zimmer and Volkamer 1984).

Explanations of symbols: [#] Hg in all biomonitors; [~] Hg in at least one biomonitor; *HBM I and II for blood and urine (HBM Commission 1999, 2009, Schulz et al. 2012); BAT for blood and urine (DFG 2009). HBM I for hair derived by Drasch et al. (2001) from the US EPA (1997) benchmark limit. HBM II for hair derived by Drasch et al. (2001) from the HBM II value for blood (HBM Commission 1999, 2009, Schulz et al. 2012) in combination with results from the Seychelles study (Davidson et al. 1998). ⁺ (0/1): 0= negative, 1= positive; (0/1/2): 0= good, 1= restricted, 2= poor performance; maximum medical score sum: 21 points.

4.3 Environmental Burden of Disease (EBD)

The DALY is a common summary measure of population health (SMPH) used within the BoD and EBD framework. Instead of traditional measures to describe the health status of populations like the number of deaths from diseases or incidence data, SMPHs combine aspects of morbidity and mortality in one metric. Health gaps are measured with DALYs by comparing given situations with an ideal situation where everyone lives up to a standard life expectancy. DALYs use time as the unit of measure to express the time lost due to premature mortality combined with the time lived in a specific health state (Prüss-Üstun et al. 2003). DALYs caused by risk factors are quantified within a CRA framework. CRA is a systematic

analysis of changes in population health as result of changes in the exposure of the population to given risk factors. For the changing exposure to risk factors, counterfactual scenarios are applied to compare a given health burden with the burden of a hypothetical scenario. The hypothetical scenario can be the absence of the risk factor (calculated using the population attributable fraction, PAF) or reduction of the exposure to a risk factor (calculated using the impact fraction, IF) (Ezzati et al. 2004).

In this thesis, DALYs were estimated as combination of years lived with disability (YLD) and years of life lost due to premature mortality (YLL). The YLD comprises the number of incident cases (a) multiplied by a DW (b) and the average duration of disability (c). The YLL is calculated by multiplying the number of deaths (d) with a standard remaining life expectancy at the age of death (e). Also for this analysis, age weights (f) and a discount rate (g) were applied for lost life years in the future to ensure comparability with the WHO GBD 2004 update (WHO 2008a)¹⁰. The DALYs calculated were related to the total population of Zimbabwe and presented as rates (DALYs/1,000 population). Those DALYs are quantified which would not occur if there had been no exposure. Scenario analyses were done to observe result variations depending on differences in data from various sources (P3).

No data was available for Zimbabwe or any other country on incident cases of chronic mercury intoxication, duration of disability, and mortality. As a result, the prevalence of chronic mercury intoxication, analyzed using the primary survey data from Zimbabwe 2004 and 2006 (Chapter 4.2), was entered into the disease modeling tool DisMod II along with data on remission and case fatality taken from the literature and official population and total mortality data. The data modeling yielded an estimator of incidence, mortality, relative risk of mortality, and duration of disease (P3).

Data on disease severity of chronic mercury intoxication was not available; therefore a provisional DW of a comparable disease was used. The following criteria describing chronic mercury intoxication were used to find a DW for a comparable health state: a) chronic condition, b) triggered by a substance, and c) causing symptoms similar to those of chronic mercury intoxication. For the preliminary EBD analysis, the DW for alcoholism was chosen as a proxy for chronic mercury intoxication (P3).

The subsequent project DiWIntox (Disability Weights for Chronic Mercury Intoxication) described in P4 (Steckling et al. 2015) aimed at deriving the missing DW when examining the

¹⁰ Although the latest DALY estimates do not use age weights and discount rates (Hornberg et al. 2013, Murray et al. 2015, Polinder et al. 2012) out of ethical considerations (Anand and Hanson 1997, Mathers et al. 2001), both were applied for the analyses to ensure comparability with the GBD 2004 update.

EBD from mercury in ASGM. A DW would improve the data basis of EBD analyses describing the health burden of gold miners. Although there are several ways to derive DWs, they all rely heavily on the disease profiles used as a basis for assessing disease severity. In the first phase of the DiWIntox¹¹ project (P4), disease profiles of chronic intoxications due to exposure to mercury from ASGM were developed by including information about the HRQoL as a generic description combined with a disease-specific description (Chapter 4.4), as recommended by a current review of DWs (Haagsma et al. 2014).

4.4 Expert elicitation and health-related quality of life (HRQoL)

In addition to the international literature (Chapter 4.1) – expert elicitation was used to develop disease profiles (P4) suitable for DW derivations following the methodological design of the formal expert elicitation protocol developed by Knol et al. (2010) and Slottje et al. (2008). The goal was to determine and describe all components of the disease profiles of intoxicated gold miners, starting with the disease label, a classification into disease stages, an explanation of the exposure situation, a list of common symptoms, and an assessment of the HRQoL (P4). Expert elicitation was conducted during a meeting in Ljubljana, Slovenia, in 2012. A group interview and presentations by several experts were part of this one-day meeting. Four Slovenian and one German interviewee with research interests in the health effects of mercury and expertise in medicine, toxicology, and/or public health participated. Two were medical doctors who had direct experiences with medical examinations of workers chronically exposed to mercury at the Idrija mercury mine (Idrija, Slovenia) or in gold mining in other countries (P4). An interview guideline with 27 questions was used to collect information on exposure and health outcomes of interest and to evaluate the meeting. Included were questions regarding the HRQoL, which was assessed using the EuroQol (EQ) questionnaire EQ-5D+C-3L. The questionnaire contains the five dimensions (5D) mobility, self-care, usual activities, pain/discomfort, anxiety/depression and is supplemented by a cognition dimension (+C) as previously applied (Stouthard et al. 1997). There were three response levels (3L): no problems (1), problems (2), and severe problems (3) (EuroQol Group 1990, Krabbe et al. 1999, van Reenen and Oppe 2015). During open consensus discussions, experts assessed chronic intoxications due to exposure to mercury in ASGM according to the six dimensions coded in the three levels. Experts were used as proxies while it was not possible to ask individuals with

¹¹ In the second phase of the DiWIntox project, the DW for the health outcome of ASG miners on the basis of the disease profiles presented in P4 is being determined. This phase started in September 2015 and is scheduled to continue until 2016. It is therefore not possible to include the final project results in this thesis.

mercury intoxication. The interview transcript and one of the expert presentations (as well as literature, see 4.1) were used as data sources for disease profiles (P4).

4.5 Practical testing of a mercury-free gold extraction procedure

In December 2013, a field project was undertaken to test a mercury-free gold extraction procedure using borax for ASGM in Kadoma, Zimbabwe. The willingness of the miners to change to another gold extraction method was tested along with the local availability of suitable materials and equipment as well as suitability of the ore for applying the mercury-free technology. A one-day theoretical workshop was held and a two-day practical demonstration given. Simple qualitative methods like trial and error and the collection of indices during discussions and observations were feasible under the field conditions (P5).

5 Main Results

Table 4 shows the main results of the individual research projects included in this thesis. The specific results from the papers, which are relevant to answer the main research question as well as the subquestions stated in Chapter 3, are summarized in four subchapters. Chapter 5.1 outlines the particular risks of children from exposure to mercury in and beyond ASGM¹². Chapter 5.2 gives the mercury body burden in selected ASGM areas¹³. Chapter 5.3 describes the health burden from mercury used in ASGM¹⁴. Chapter 5.4 shows the result of the practical testing of a mercury-free extraction procedure¹⁵. The chapter structure corresponds to the four subquestions defined while evidence to answer the overarching subquestion I is included in every chapter.

¹² Includes results of P1; contributes to subquestion I, objective a; subquestion III, objective i.

¹³ Includes results of P2, P3; contributes to subquestion I, objectives b, c; subquestion II, objectives f, g, h.

¹⁴ Includes results of P3, P4; contributes to subquestion I, objectives b, c, d; subquestion III, objectives j, k, l, m.

¹⁵ Includes results of P5; contributes to subquestion I, objective e; subquestion IV; objectives n, o, p.

Table 4: Summary of the main results of the five papers forming the basis of this thesis

Paper (P)	Main results
P1: Bose-O'Reilly et al. (2010c)	Mercury is highly toxic to humans and particularly to the development of children. There are many pathways of exposure to mercury for children; one important example is ASGM. Direct (child labor) or indirect (e.g., mining parents) exposure to mercury used in ASGM is possible. Prevention is the key to reduce exposure.
P2: Steckling et al. (2011)	Female gold miners and residents not involved in mining but living in mining areas of child-bearing age in Mongolia showed elevated mercury values, especially in urine (median: 3 and 7 µg/g creatinine; maximum: 80 and 300 µg/g creatinine, respectively). 64 and 36% of miners and residents not involved in mining but living in mining areas, respectively, exceeded the threshold value HBM I for creatinine corrected urine.
P3: Steckling et al. (2014a)	Male and female miners in Zimbabwe showed elevated mercury values in blood, urine, and hair (urine; median: 26 µg/g creatinine; maximum: 670 µg/g creatinine). 82% of miners exceeded the threshold value HBM I for creatinine corrected urine. 90% of miners exceeded a medical score sum of 4 points. Chronic mercury intoxication was diagnosed in 72% of miners (with subgroup differences ranging from 26 to 91%). A total of 95,400 DALYs (8 DALYs/1,000 population) due to the use of mercury in ASGM was estimated for Zimbabwe, 2004. Scenario analyses yielded a range of 6 to 12 DALYs/1,000 population.
P4: Steckling et al. (2015)	250 terms describing 85 distinguishable health effects of CMMVI of adults exposed to metallic mercury vapor were found. 29 health effects were common and frequently described and assigned to moderate and/or severe CMMVI. HRQoL was assessed by experts and rated with the EQ-5D+C-3L codes 121222 for moderate and 233333 for severe cases of CMMVI.
P5: Steckling et al. (2014b)	Miners and officials from ministries and agencies showed interest in the mercury-free gold extraction procedure. It was possible to purchase material and equipment necessary for mercury-free gold extraction in Kadoma, Zimbabwe. Testing was successful yielding 1.11 grams of gold from 500 kilogram ore.
Abbreviations: ASGM: artisanal small-scale gold mining; CMMVI: chronic metallic mercury vapor intoxication; DALYs: disability-adjusted life years; EQ-5D+C-3L: EuroQol questionnaire with 5 dimensions (mobility, self-care, usual activities, pain/discomfort, anxiety/depression) accompanied by the cognition add-on questionnaire, coded in 3 levels for responses (no problems (1); problems (2); severe problems (3)); HBM I and II: human biomonitoring values I and II from the HBM commission of the German Environment Agency; P1 to P5: papers this thesis is based on; HRQoL: health-related quality of life	

5.1 Children as particularly vulnerable subgroup at risk

Children are particularly vulnerable to mercury. The relevant information was reviewed in P1 (Bose-O'Reilly et al. 2010c) and the evidence relevant to this thesis is summarized below. The original references cited in P1 are also included in this chapter.

Children can be exposed to mercury from a variety of sources. High exposure situations are widespread in ASGM since child labor is common in Africa, Asia, and South America (Eisler 2004, UNEP 2002). Estimates of the number of child workers in ASGM total up to 1 million for all areas together¹⁶. The exposure to mercury is either direct by occupational involvement of the children themselves (Eisler 2004, UNEP 2002) or secondary, as result from exposure to parents who work as miners and/or amalgamate ore at home¹⁶ (P1).

¹⁶ ILO: Mining and quarrying [Website]. Access: <http://www.ilo.org/ipecc/areas/Miningandquarrying/lang--en/index.htm> [last access March 12, 2016].

Occupational ASGM exposure is due to elemental mercury. However, elemental mercury released during gold mining is transformed into methylmercury in the environment (Eisler 2004). Organic mercury is the most dangerous form. Communities living near ASGM regions are exposed to methylmercury as a result of gold mining (Olivero et al. 2002, Santos et al. 2002). Fish consumption is the main means of exposure to methylmercury (Al-Saleh 2009) (P1).

Children playing on the ground with frequent hand-to-mouth contact increase the likelihood of exposure. Children are often attracted to liquid mercury because of its properties and appearance (MacLehose et al. 2001) and tend to play with it (Azziz-Baumgartner et al. 2007). Unborn children also are at risk if their mothers are exposed to mercury during pregnancy. Mercury enters the placenta and accumulates in the fetus (Harada 1995). Another exposure pathway for children is breastfeeding if the mother's milk is contaminated with mercury (Amin-Zaki et al. 1981, ATSDR 1999, Bjornberg et al. 2005, Bose-O'Reilly et al. 2008b, Grandjean et al. 1995, Yoshida et al. 1992) (P1).

Unborn children and infants are at particular risk from mercury because of its developmental toxicity. The healthy development of the central nervous system is particularly endangered (Rice and Barone 2000). Mercury-related damage is likely to be permanent (Grandjean 2007, Murata et al. 2004). Due to children's growth and development, their susceptibility is different from that of adults (Sly and Pronczuk 2007, WHO 2006). Clinical symptoms of mercury intoxication were observed in children exposed to mercury in ASGM (Akagi et al. 2000, Bose-O'Reilly et al. 2008a, Grandjean et al. 1999) (P1).

In P1 it is concluded that ideally, children and adults alike should avoid all exposure to mercury while prevention is the key to reduce the burden. Children should not work as gold miners or live near mining areas. Furthermore, separation of housing and mining is a necessity, and children should by all means be kept from playing with mercury.

P1 highlights that children, unborn children, pregnant and breastfeeding women are important subgroups at risk of exposure to mercury. Following on the insights in P1, the subsequent papers focus on exposure to mercury of women of child-bearing age (P2, P3) and on child workers (P3). P1 also emphasizes that the behavior of other subgroups is related to the exposure of children (e.g., amalgamation at home due to parents working as miners). Consequently, P3 also discusses male miners as the main ASGM subgroup.

5.2 The mercury body burden in artisanal small-scale gold mining (ASGM)

The 198 women surveyed in Mongolia were between 15 and 35 years old. The 64 female miners had worked with mercury for an average of 4 years (minimum 1 year to maximum 12 years). Of the respondents 60% reported storing mercury at home and 70% reported keeping the clothes they wore at work at home. Also, 11% of the 92 residents not involved in mining but living in mining areas reported storing mercury at home. The subgroups miners (n= 64), residents not involved in mining but living in mining areas (n= 92), and controls (n= 42) did not differ significantly regarding other confounding factors such as amalgam fillings, fish consumption, alcohol, or smoking. However, 19 individuals in the mining areas reported drinking alcohol at least once a month, while none in the control region reported doing so. Only 8 individuals reported eating fish at least once a month (P2).

The sample from Zimbabwe included 122 male and 59 female miners aged 9 to 75 years and a control group of 24 men and 67 women aged 11 to 59 years. All miners had worked with mercury for 1 to 23 years (mean 4 years). Besides mercury, 41% of miners also used cyanide. Eleven miners (6%) reported using retorts to capture the mercury vapor. Nearly all (98%) miners stored their working clothes at home, and 84% stored mercury at home. Miners and controls differed significantly regarding the confounding factors fish consumption, alcohol, and smoking, which were more prevalent amongst miners (P3).

Table 5 shows the results of tests done on blood, hair, and urine samples of occupationally exposed miners in Mongolia (females; P2) and Zimbabwe (males and females; P3), residents not involved in mining but living in mining areas in Mongolia (P2), and male and female control groups in both countries (P2, P3). Women in ASGM in Mongolia showed elevated mercury urine levels with median values of 3 and 4 $\mu\text{g/l}$ (3 and 7 $\mu\text{g/g}$ creatinine) but maximum values up to 80 and 50 $\mu\text{g/l}$ urine (80 and 300 $\mu\text{g/g}$ creatinine) for residents not involved in mining but living in mining areas and miners, respectively (P2). Occupationally exposed male and female miners in Zimbabwe showed a distinctly higher body burden than did the subgroup in Mongolia with median mercury urine concentrations of 26 $\mu\text{g/l}$ (26 $\mu\text{g/g}$ creatinine) and maximum concentrations of 1,530 $\mu\text{g/l}$ and 670 $\mu\text{g/g}$ creatinine, respectively. In the sample from miners in Zimbabwe, mercury levels in blood and hair also were elevated, with a median level of 11 $\mu\text{g/l}$ and 3 $\mu\text{g/g}$ and a maximum level of rounded 100 $\mu\text{g/l}$ and 110 $\mu\text{g/g}$, respectively (P3). Control groups in both countries showed low background mercury concentrations in human specimens, mostly below 1 $\mu\text{g/l}$ urine or blood or below 1 $\mu\text{g/g}$ hair or even below the level of detection (LOD) (P2, P3).

Table 5: Human biomonitoring (HBM) concentrations of data from Mongolia and Zimbabwe and classification into exposure limit values (adapted from Steckling et al. (2011) and Steckling et al. (2014a))

Human biomonitoring	Controls		Environmentally exposed	Occupationally exposed	
	Mongolia	Zimbabwe	Mongolia	Mongolia	Zimbabwe
Hg in urine (µg/l)	n= 42	n= 91	n= 92	n= 64	n= 181
Mean	<1	<1	5	6	91
Median	<LOD	<LOD	3	4	26
Range (min.-max.)	<LOD - 1	<LOD - 9	<LOD - 79	<LOD - 52	<LOD - 1,530
95 th percentile	<1	1	11	18	377
Hg in urine, exposure limit values					
Below HBM I	42 (100%)	90 (99%)	82 (89%)	52 (81%)	38 (21%)
Between HBM I and HBM II	0 (0%)	1 (1%)	8 (9%)	11 (17%)	49 (27%)
Above HBM II	0 (0%)	0 (0%)	2 (2%)	1 (2%)	94 (52%)
Hg in urine corrected for creatinine (µg/g cr.)	n= 0	n= 80	n= 85	n= 58	n= 181
Mean	/	<1	8	19	58
Median	/	<LOD	3	7	26
Range (min.-max.)	/	<LOD - 4	<1 - 79	<1 - 311	<LOD - 667
95 th percentile	/	1	26	69	215
Hg in urine (cr.), exposure limit values					
Below HBM I	/	80 (100%)	54 (64%)	21 (36%)	32 (18%)
Between HBM I and HBM II	/	0 (0%)	23 (27%)	27 (47%)	47 (26%)
Above HBM II	/	0 (0%)	8 (9%)	10 (17%)	102 (56%)
Hg in blood (µg/l)	n= 42	n= 48	n= 92	n= 64	n= 152
Mean	<1	<1	<1	1	19
Median	<LOD	<1	<1	<LOD	11
Range (min.-max.)	<LOD - 4	<LOD - 2	<LOD - 8	<LOD - 10	<LOD - 101
95 th percentile	2	2	1	2	58
Hg in blood, exposure limit values					
Below HBM I	42 (100%)	48 (100%)	91 (99%)	63 (98%)	34 (22%)
Between HBM I and HBM II	0 (0%)	0 (0%)	1 (1%)	1 (2%)	56 (37%)
Above HBM II	0 (0%)	0 (0%)	0 (0%)	0 (0%)	62 (41%)
Hg in hair (µg/g)	n= 35	n= 79	n= 92	n= 64	n= 158
Mean	<1	<1	<1	<1	9
Median	<1	<1	<1	<1	3
Range (min.-max.)	<1 - 1	<1 - 3	<1 - 2	<1 - 3	<1 - 112
95 th percentile	<1	<1	1	1	34
Hg in hair, exposure limit values					
Below HBM I	35 (100%)	77 (97%)	90 (98%)	63 (98%)	18 (11%)
Between HBM I and HBM II	0 (0%)	2 (3%)	2 (2%)	1 (2%)	84 (53%)
Above HBM II	0 (0%)	0 (0%)	0 (0%)	0 (0%)	56 (35%)
Abbreviations: µg/l: microgram per liter; µg/g: microgram per gram; cr.: creatinine; HBM I and II: human biomonitoring values I and II from the HBM commission of the German Environment Agency; LOD: limit of detection; max.: maximum; min.: minimum					
Data sources: The data from Mongolia was taken from a health and HBM data collection as part of an environmental epidemiological cross sectional study conducted in Mongolia in September 2008 and funded by WHO and MoH. For Zimbabwe, the data was taken from the Global Mercury Project (GMP) which was conducted by UNIDO in 2004 (Bose-O'Reilly et al. 2004, Bose-O'Reilly et al. 2008a), and from a health and biomonitoring project focusing on women of child-bearing age and their infants conducted by the Ludwig-Maximilians-University Munich (LMU) in 2006 (Baeuml et al. 2011).					
Further explanation: A sum of less than 100% is due to rounding. LOD: The limit for determining total mercury in urine and blood was 0.20 µg/l, and 0.02 µg/g in hair from a 100 mg hair sample. Values below the detection limit were included in the statistical analyses with one-half the detection threshold.					
Threshold values: The HBM I and HBM II values for blood and urine were taken from the HBM commission of the German Environment Agency (HBM Commission 1999, 2009, Schulz et al. 2012). The HBM I value for hair was derived by Drasch et al. (2001) from the U.S. EPA benchmark limit (US EPA 1997). The HBM II value for hair was derived by Drasch et al. (2001) from the HBM II value for blood (HBM Commission 1999, 2009, Schulz et al. 2012) together with results from the Seychelles study (Davidson et al. 1998). The data from Zimbabwe was also compared with the BAT value (biological workplace tolerance level) for blood and urine as given by the German Research Foundation (DFG 2009). For details see Steckling et al. (2014a).					

Table 5 also gives comparisons of mercury in human specimens with the German HBM values HBM I and HBM II (Schulz et al. 2007). No samples of the control group in Mongolia (P2), and 3 outlier samples of the control group in Zimbabwe (P3) showed a mercury body burden above HBM I. The Mongolian urine sample exceeded the HBM I values with 11 and 19% (36 and 64% when creatinine-corrected) of residents not involved in mining but living in mining areas and miners, respectively. Mercury in blood and hair is very low for both exposed groups in Mongolia in a range comparable to the background concentration of controls (P2). On the contrary, around 80 to 90% of the samples of the occupationally exposed Zimbabweans exceeded the threshold values, observable in urine, blood, and hair (P3).

Increased mercury values in the human specimens of the gold miners from Mongolia and Zimbabwe were reported in P2 and P3. Besides the focus on the mercury body burden in ASGM, P3 includes further analyses of the sample of gold miners in Zimbabwe for insights into the gold miners' health burden, described in Chapter 5.3.1 and 5.3.2.

5.3 The health burden from exposure to mercury used in ASGM

P3 and P4 contain evidence for health effects caused by the exposure to mercury used in ASGM. Information is given on the epidemiology of chronic mercury intoxication (P3, Chapter 5.3.1), an estimate of its EBD (P3, Chapter 5.3.2), and development of disease profiles of chronic metallic mercury vapor intoxication (P4, Chapter 5.3.3).

5.3.1 The epidemiology of chronic mercury intoxication in ASGM

Chronic mercury intoxication was examined using statistical and epidemiological analyses of health effects and combining it with HBM data to identify cases indicating intoxication and to determine prevalence. Further, data on case fatalities and remission rates was collected from the literature. Finally, data modeling was applied using the modeling tool DisMod II by including the generated and the collected data as input (P3).

Both, the miners and the controls investigated during the two projects in Zimbabwe in 2004 and 2006 showed health effects which can be caused by mercury, although miners showed these health effects more frequently. Thus, 3% of controls and 19% of miners reported a metallic taste during anamnesis and during clinical investigation, 19% of controls and 35% of miners showed ataxia of gait. In these examples controls and miners differed significantly, while analysis of most of the other health indicators did not reveal significant differences. However, when summarizing the results of the health effects in a medical score sum, the subgroups differed significantly with the miners scoring higher than the controls. 90% percent of

the miners exceeded a medical score sum of 4 points, while less than 60% of the controls did (P3).

The results of health effects analyses were combined with data on the mercury body burden (Chapter 5.2) to identify cases of chronic mercury intoxication. None of the controls was diagnosed with chronic mercury intoxication. The miners showed a total prevalence of 72% with subgroup differences ranging from 26% for female miners aged 15 to 24 years up to a prevalence of 91% for men aged 15 to 24 years. The total sample prevalence for female miners was 40%. Women aged 25 and older reached a prevalence of 52%. Prevalence was consistently high in male miners, with the lowest prevalence of 88% for those aged 25 to 34. Children showed a prevalence of 76% (P3).

The sample prevalence was extrapolated to all of Zimbabwe to determine the population prevalence using estimates of exposure distribution from the literature. It was assumed that 350,000 miners (Dreschler 2002, GEF et al. 2002, IIED and WBCSD 2002, ILO 1999) were involved in gold mining in Zimbabwe in 2004. The number includes 15% of child workers. 30% of the adult gold miners were assumed to be women. According to the information used, 3% of the total population in Zimbabwe in 2004 was occupationally involved in gold mining. Separated into subgroups, 2% of the female and 4% of the male population, as well as 4% of the adult population and 3% of children were involved. The greatest occupational involvement (10%) was estimated for males aged 25 to 41 years; the lowest involvement (1%) was assumed for females aged 9 to 14 years and 42 years and older. The females with the highest exposure with 4% were women aged 25 to 34. The lowest occupational involvement in men was assumed for those aged 9 to 14 years, with 4% of the population in that age group (P3).

Applying the sample prevalence (72%) to the exposure distribution (3%) yields a population prevalence of chronic mercury intoxication of 2% of the total population. Subgroup analyses yielded a range for males from 3% (9 to 14 years and 42 years and older) to 9% (25 to 34 years), and for females from 1% (all age groups except those aged 25 to 34) to 2% (25 to 34 years). A prevalence of nearly 2% of the children (9 to 14 years) was assumed; 3% of boys and 1% of girls were intoxicated (P3).

The epidemiology of chronic mercury intoxication was further described using indices from the literature and to model unavailable data. According to the literature, the case fatality of chronic mercury intoxication is zero (Cragle et al. 1984) and there is no remission (Buckell et al. 1993, Drasch et al. 2004, Nordberg 1998, WHO 1990, 2003). Using the population preva-

lence, case fatality, and remission data as input into DisMod II, the incidence, mortality, and duration of chronic mercury intoxication were modeled (P3).

The data regarding the epidemiology of chronic mercury intoxication was then used to analyze the EBD (Chapter 5.3.2).

5.3.2 The EBD of chronic mercury intoxication in ASGM

The EBD – or more precise the occupational BoD – in terms of DALYs attributable to mercury intoxication due to the use of mercury in ASGM in Zimbabwe, 2004, were estimated using the epidemiological data described in Chapter 5.3.1. Furthermore, population data and a standard remaining life expectancy at the age of death were included. A DW for chronic mercury intoxication was not available and the DW of alcoholism was chosen as the best proxy. Age weights and a discount rate were applied for comparability with the WHO GBD 2004 update (WHO 2008a) (P3).

According to the main analysis, a total of 95,400 DALYs (8 DALYs/1,000 population) were caused by chronic mercury intoxication due to an occupational exposure to mercury in gold mining in Zimbabwe in 2004. The highest burden was estimated for male miners aged 9 to 14 years, with a maximum of 28 DALYs/1,000 population. The most strongly affected women were those aged 25 to 34 years, with 7 DALYs/1,000 population. Female miners over 35 years showed a burden of less than 1 DALY/1,000 population (P3; Table 6).

Table 6: Disability-adjusted life years (DALYs) attributable to the use of mercury in artisanal small-scale gold mining (ASGM) in Zimbabwe in 2004 by subgroup (adapted from Steckling et al. 2014a, p. 12)

Age (years)	Males			Females			Total		
	Population*	DALYs	DALYs per 1,000	Population*	DALYs	DALYs per 1,000	Population*	DALYs	DALYs per 1,000
0-8	1,540,000	1,200	<1	1,529,000	500	<1	3,069,000	1,700	<1
9-14	1,042,000	28,900	28	1,038,000	3,400	3	2,080,000	32,300	16
15-24	1,533,000	38,200	25	1,552,000	6,700	4	3,085,000	44,900	15
25-34	871,000	10,100	12	870,000	6,400	7	1,741,000	16,500	9
35-41	293,000	<100	<1	353,000	<100	<1	646,000	<100	<1
≥42	788,000	<100	<1	1,083,000	<100	<1	1,870,000	<100	<1
Total	6,067,000	78,400	13	6,425,000	17,000	3	12,492,000	95,400	8

Abbreviations: DALYs: disability-adjusted life years.
Explanation of symbols: * Zimbabwe's population in 2004; source: world population prospects (UN 2009).
Further explanations: The results of this analysis rest on the assumptions determined in Steckling et al. (2014a). Changing the assumptions will require changing the analysis. All numbers are rounded.

Scenario analyses yielded total minimum and maximum estimates of 6 and 12 DALYs/1,000 population, respectively. The lowest estimate was obtained by applying an alternative DW

(0.134 rather than 0.180). The highest number of DALYs was estimated using an average maximum prevalence of 3% (rather than 2%). The maximum prevalence is based on the assumption that 500,000 ASG miners (rather than 350,000) were active in Zimbabwe in 2004, including 2% children (rather than 15%) and 11% of women (rather than 40%) (P3).

Data availability allowed a preliminary estimate of DALYs due to chronic mercury intoxication in ASGM for Zimbabwe in 2004. One important reason for the preliminary character of the analysis is the missing DW for chronic mercury intoxication. Scenario analyses revealed a high sensitivity when using another DW. The research need was discussed in P4 as disease profiles for DW derivation were developed.

5.3.3 HRQoL and disease profiles

Disease profiles were developed for adults chronically exposed to metallic mercury vapors, which corresponds to the main route of exposure for ASGM workers. It was feasible to distinguish between moderate and severe cases of chronic metallic mercury vapor intoxication (CMMVI). The analysis of 10 selected sources (interview transcript, presentation, and 8 literature reviews) identified more than 250 terms describing 85 distinguishable health effects of CMMVI. Twenty-nine health effects were identified as common and frequently mentioned and were classified – some with varying symptom severity – as moderate and/or severe CMMVI (P4).

The HRQoL related to CMMVI was assessed by experts, who used the EQ-5D+C-3L codes 121222 for moderate and 233333 for severe CMMVI. Table 7 shows the disease profiles of moderate and severe CMMVI with a disease-specific and a generic description (P4).

The disease profiles developed in P4 are suitable as health state descriptions for DW derivation. Hence, the results of P4 improve the data basis for EBD analyses as made in P3. The papers P1, P2, P3, and P4 used different approaches to describe the burden from exposure to mercury used in ASGM. The results of the 4 papers underlined the urgent need to reduce exposure to mercury from ASGM. Thus, the project described in P5 aimed at testing a mercury-free gold extraction procedure in Kadoma, Zimbabwe.

Table 7: Disease profiles of moderate and severe cases of chronic metallic mercury vapor intoxication (CMMVI) (adapted from Steckling et al. 2015, p. 5)

Disease label	Chronic Metallic Mercury Vapor Intoxication (CMMVI)	
Disease stage	Moderate case	Severe case
Disease-specific description (including exposure and health situation)	<p>Adults with a high mercury body burden caused by chronic inhalation of metallic mercury vapor who show several of the following symptoms:</p> <ul style="list-style-type: none"> • Slight tremor of fingers, hands, and limbs; coordination problems; dysfunction of movement control; weakness • Reflexes abnormalities; peripheral nerve abnormalities; sensory disturbances • Sleep disorders; irritability; nervousness; fatigue; memory impairment; difficulty in concentration; shyness; depressive mood; loss of confidence; lack of self-control • Renal effects like enzymuria, proteinuria, and glomerular dysfunction, increased urinary excretion of N-acetyl-β-glucosaminidase (NAG) • Loss of appetite; salivation • Immunological changes 	<p>Adults with a very high mercury body burden caused by chronic inhalation of metallic mercury vapor who show several of the following symptoms:</p> <ul style="list-style-type: none"> • Pronounced tremor in several parts of the body; severe coordination problems; dysfunction of movement control; weakness • Polyneuropathy • Insomnia; hyperirritability; nervousness; fatigue; loss of memory; difficulty in concentration; extreme shyness; depression; loss of confidence; lack of self-control; social avoidance • Abnormal renal function with enzymuria, high proteinuria, glomerular dysfunction, and rising urinary excretion NAG • Anorexia; excessive salivation; gingivitis; stomatitis • Immunological changes • Difficulty seeing
Generic description (EQ-5D+C-3L)	<ul style="list-style-type: none"> • No problems in walking (1) • Some problems with self-care (2) • No problems with performing usual activities (1) • Moderate pain or discomfort (2) • Moderately anxious or depressed (2) • Some problems in cognitive functions (2) 	<ul style="list-style-type: none"> • Some problems in walking about (2) • Not able to wash or dress themselves (3) • Not able to perform usual activities (3) • Severe pain or discomfort (3) • Extremely anxious or depressed (3) • Severe problems in cognitive functions (3)
<p>Abbreviations: EQ-5D+C-3L: EuroQol questionnaire with 5 dimensions (mobility, self-care, usual activities, pain/discomfort, anxiety/depression) accompanied by the cognition add-on questionnaire, coded in 3 levels for responses (no problems (1); problems (2); severe problems (3)); NAG: N-acetyl-β-glucosaminidase</p>		

5.4 Mercury-free gold extraction

All 50 local miners and officials from ministries and agencies, who were invited to the theoretical workshop in Kadoma, Zimbabwe, on the 4th of December, 2013, attended the event. The participants expressed their interest in the mercury-free gold extraction procedure and spent the day listening to the lectures and asking for demonstrations. They were interested in details in the differences between amalgamation and the mercury-free method, the applicability of available equipment (e.g., mills) when using the mercury-free method, as well as the availability and price of borax and the quantity needed. They also were interested in possible health effects of both mercury and borax. Close to 40 decided to spend another two days (December 5th and 6th, 2013) at the workshop and organized transportation to attend the practical testing (P5).

Figure 1 shows a technical drawing of the mercury-free gold extraction procedure¹⁷. The material necessary for the mercury-free gold extraction procedure was bought locally near Kadoma town. Carpets and blow torches were not readily available. An artificial turf was used as a carpet substitute, but the nearest blow torch was several kilometers away from the testing site. The testing resulted in a 1.11 gram button of gold from 500 kg ore. The miners noticed that the mercury-free procedure captured more fine-grained gold particles than did amalgamation (P5).

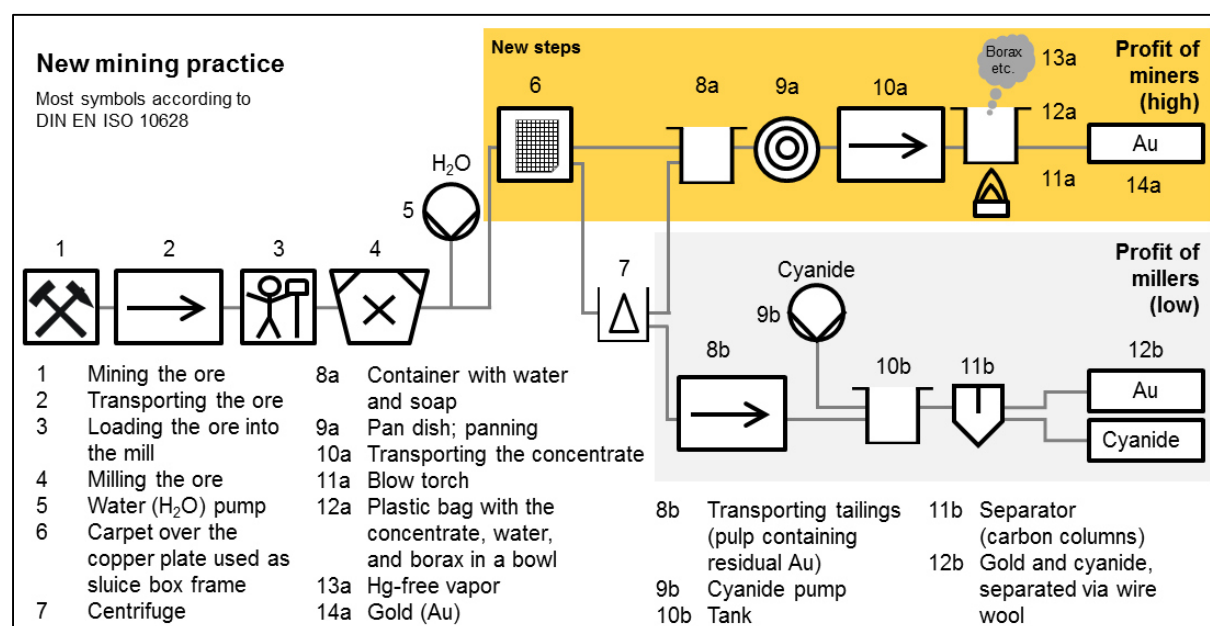


Figure 1: Technical drawing of the mercury-free gold extraction procedure using borax demonstrated during the field project in Kadoma, Zimbabwe, in 2013 (Steckling et al. 2014b, p. 57)

6 Discussion

Five peer-reviewed scientific papers provide evidence to improve the understanding of the human health risk of using mercury in ASGM. This evidence was obtained by using different methods and materials to describe the risk and by testing a way to reduce this risk. This thesis includes country-specific results for Mongolia (P2) and Zimbabwe (P3, P5) as well as results without regional context (P1, P4). In the following, the main research question is first answered in general before the findings for subquestion II (*body burden*), III (*health burden*), and IV (*reducing the risk*) are shown, discussed, and integrated in the state of research one after another. Subquestion I (*relevant subgroups*) has an overarching character examining the *relevance of different subgroups when aiming for describing and reducing the human health*

¹⁷ An additional technical drawing of the amalgamation procedure is presented in Steckling et al. (2014b).

risk from mercury used in ASGM and is thus answered along with the other subquestions. Limitations and needs for future research are also discussed.

All five papers compiled in this thesis contribute to answering the main research question, i.e., *how to describe and reduce the human health risk of mercury used in ASGM*: The human health risk associated with using mercury in ASGM can be described as *considerable*, *subgroup-specific*, and, in fact, *reducible*.

The health risk is *considerable* because of the particular risk to children (P1), the high mercury concentrations in human specimens obtained from residents not involved in mining but living in mining areas (P2) and miners (P2, P3), the high prevalence of intoxications and EBD in miners (P3), the extensive range of possible health symptoms, and the HRQoL reduced by mercury intoxication (P4). The health risk is *subgroup-specific* because of the particular risk to children and the relevance of the behavior of other subgroups on children's exposure (P1), the human body burden detectable in miners and residents not involved in mining but living in mining areas varying by sex and age (P2, P3), the prevalence of intoxications and EBD in miners varying by sex and age (P3), and the extensive range of possible health symptoms which can, but do not have to, occur in individuals as a result from exposure to mercury (P3, P4). The health risk is *reducible* because a mercury-free gold extraction procedure has been tested successfully (P5).

The key finding of *the mercury body burden in ASGM areas* (subquestion II) is that the sample of women of child-bearing age involved in mining or living in mining areas in Bornuur district and Jargalant district, Mongolia (P2), as well as the sample of adult and child male and female miners in Kadoma, Zimbabwe (P3), showed increased mercury concentrations in their specimens above health-related exposure limit values. The subgroup with the highest body burden was the sample from Zimbabwe. However, the subgroups analyzed for Mongolia and Zimbabwe are not comparable. Although, both datasets included data of women of child-bearing age, in the dataset from Zimbabwe this subgroup was included in a sample with further subgroups (men, children, women in other age groups). A separate analysis of the different subgroups included in the dataset from Zimbabwe was not done, which impedes directly comparing the HBM data of women of child-bearing age, whose data are integrated in the analysis of both countries.

The data taken for this thesis were further analyzed in other contexts, as noted in the state of research (Chapter 2). Baeuml et al. (2011) analyzed the samples from Zimbabwe in 2004 and 2006 separately (rather than together, as was done for P3) by focusing on the age group 15 to

60 years (rather than 9 to 75, as was done for P3) and combining data from residents not involved in mining but living in mining areas (excluded from the analysis in P3) and miners and compared it with the combined data of miners and residents not involved in mining but living in mining areas from Mongolia in 2008 (analyzed separately for P2). Additionally, HBM data for samples in ASGM areas from Indonesia, the Philippines, and Tanzania are presented. In this comparison, the sample from Zimbabwe (2004) showed the highest median and the second highest maximum urine mercury concentrations (1,530 $\mu\text{g/l}$) after Kalimantan in Indonesia (maximum 5,240 $\mu\text{g/l}$) (Baeuml et al. 2011).

When considering available HBM data from ASGM communities around the world, great differences between mercury concentrations in human specimens from gold mining communities were found (Gibb and O'Leary 2014, Kristensen et al. 2014). The highest mean concentration in creatinine-corrected urine was found for dealers of unrefined gold in Burkina Faso (299 $\mu\text{g/g cr.}$) (Tomicic et al. 2011) (reviewed by Gibb and O'Leary 2014). Burkina Faso has an excessively high mercury consumption per unit of gold with a Hg:Au ratio of 70 (compare Chapter 1; Seccatore et al. 2014). Further studies also analyzed data from gold dealers and found the highest mercury concentrations in this subgroup (Kristensen et al. 2014). Gold dealers are responsible for refining gold, which is done by heating it to evaporate residual mercury (Tomicic et al. 2011). These results show that the refining process is a major source of exposure to mercury and highlight the necessity to investigate this subgroup in Mongolia and Zimbabwe, which has not been done yet.

The highest mean concentration for miners are reported for Venezuela (233 $\mu\text{g/g cr.}$) (Veiga et al. 2005) (reviewed by Kristensen et al. 2014). The lowest human body burden for gold miners was reported for Tanzania, with a mean of 1.21 $\mu\text{g/g cr.}$, although, these miners were not involved in amalgam smelting (Bose-O'Reilly et al. 2010b) (reviewed by Gibb and O'Leary 2014). By comparison, the mean concentration in the sample from Mongolia was 8 $\mu\text{g/g cr.}$ for residents not involved in mining but living in mining areas and 19 $\mu\text{g/g cr.}$ for miners (P2) and 58 $\mu\text{g/g cr.}$ for miners in Zimbabwe (P3). These high differences in mercury concentrations in human specimens might be due to the gold extracting methods used, use of safety equipment, the intensity of gold mining, or the methodology of the studies (Kristensen et al. 2014).

The samples from Mongolia and Zimbabwe revealed differences in the kind of exposure (P2, P3). 80 to 90% of the mercury concentrations in samples from Zimbabwe exceeded the threshold values for blood, hair, and urine (P3). Miners, residents not involved in mining but living in mining areas, and controls in Mongolia differed significantly regarding mercury con-

centrations in blood, hair, and urine. However, threshold exceedances in the samples from Mongolia are nearly limited to urine samples. 19 and 11% of urine samples (64 and 36% of creatinine-corrected samples) of miners and residents not involved in mining but living in mining areas, respectively, exceeded the HBM I value. Not more than 2% exceed HBM I when considering blood and hair in the sample from Mongolia (P2). Mercury in urine indicates chronic exposure to inorganic mercury, hair samples reflect mainly chronic exposures to organic mercury, and blood mercury concentrations reflect predominantly acute exposures to both organic and inorganic mercury (Drasch et al. 2004). Hence, exposures to organic mercury and acute exposures are negligible in the sample from Mongolia. For the miners in Zimbabwe, the urine mercury concentrations also are the most remarkable, but elevated blood and hair mercury concentrations were also observed. This result is further confirmed by taking into account fish consumption. Eating fish at least once a month is not common in Mongolia (P2) but very common amongst gold miners in Zimbabwe (P3). This double exposure of miners in Zimbabwe to elemental mercury and methylmercury (P3) is especially alarming and is seen in other countries as well. Furthermore, exposure to methylmercury through contaminated fish is also a particular risk to the population not involved in gold mining (Gibb and O'Leary 2014). The low concentrations in blood might represent a low acute exposure, which could be due to the seasonal character of gold mining in Mongolia (The World Bank 2006).

In summary, this thesis provided HBM data for samples of gold miners in Mongolia and Zimbabwe and residents not involved in mining but living in mining areas in Mongolia.

In order to answer subquestion III – for *the health burden due to mercury exposure in ASGM* – several key findings are discussed in the following. (Unborn) children are particularly vulnerable to mercury exposures. They are exposed both directly and indirectly to mercury used in ASGM, while several subgroups (pregnant and breastfeeding women, parents working as miners, etc.) influence the children's exposure (P1). Other analyses in this thesis underscore this additional risk of children (and other family members), while 60 and 70% of the investigated sample in Mongolia reported storing mercury and their working clothes at home, respectively (P2). In Zimbabwe, 84% reported storing mercury at home and nearly all miners reported storing working clothes at home (P3). Ohlander et al. (2013, 2015) have recently confirmed an additional risk to children in gold mining, where the highest risk of exposure in children (odds ratio: 3.5, confidence interval: 1.2 to 9.9), calculated using mercury concentrations in fingernails, was found to be children playing in a house where someone was working with mercury. Hence, interventions aimed at reducing the exposure of children to mercury used in gold mining must take several subgroups into account.

A further possibility describing the health burden from mercury used in ASGM came from the analysis of health effects, its summary in a medical score sum, and its combination with HBM data to diagnose cases of intoxication. P3 confirmed the use of both health and HBM data to diagnose cases of intoxication, as recommended by Drasch et al. (2001). Analyzing health effects alone resulted in a mixed picture (health effects in both, miners and controls) but with a clear tendency (health effects more frequent in miners than in controls). Some controls showed many of the 21 health indicators which are probably related to mercury. However, in nearly all cases, more miners than controls showed these health effects. After combining of health and HBM data, it could no longer be assumed that health effects in controls were caused by mercury. None of the controls was diagnosed with chronic mercury intoxication and negligible or undetectable quantities of mercury were found in their human specimens (P3).

The diagnostic algorithm developed by Drasch et al. (2001) was first applied to a sample of gold miners in the Philippines yielding a prevalence of chronic mercury intoxication of 72%, which is of the same dimension seen in Zimbabwe (also 72%). In Indonesia, a prevalence of 55 to 62% was determined (Bose-O'Reilly et al. 2010a, Pereira Filho et al. 2004) and amalgam smelter in Tanzania showed a prevalence of 24% (Bose-O'Reilly et al. 2010b). In other samples, chronic mercury intoxication was diagnosed using either HBM or health data but not both in combination (Matchaba-Hove et al. 2001, Tomicic et al. 2011)

The presence of several possibly mercury-related health symptoms in mercury-unexposed controls is probably due to very diffuse symptoms of chronic mercury intoxication (Grandjean 2008). This was highlighted by the review described in P4, which identified 85 distinguishable symptoms of chronic intoxications due to metallic mercury vapor (P4). Several of these possible symptoms might have other causes than mercury. For example, aside from mercury, tremor can also be caused by neurological disorders (e.g. multiple sclerosis, stroke), liver failure, drug use, alcohol abuse (or withdrawal), or overactive thyroid. Tremors can also be inherited (NIH 2012). Thus, identifying health effects from substances is difficult. This is further aggravated by a low awareness of the problem and limited education of the miners, who may overlook health signs caused by mercury exposure. Especially slowly occurring and progressing effects due to chronic low exposures might obscure the hazardous potential of mercury (Zolnikov 2012). Hence, information about the mercury body burden is necessary to identify cases of mercury intoxication clearly.

Another key finding for subquestion III is that the EBD in adult and child male and female miners in Zimbabwe is high. Particularly males (with a total of 13 DALYs/1,000 population

in comparison to 3 DALYs/1,000 population in women) and male child and young adult workers in particular (28 and 25 DALYs/1,000 population for the age groups 9 to 14 and 15 to 24 years) are the groups with the highest burden (P3). Extreme subgroup differences already had been observed when determining the prevalence (from 26% of female miners aged 15 to 24 years to 91% of males aged 15 to 24 years). When considering the subgroup results, the following need to be highlighted. In combination with the results from P1, which reviews the particular risk of mercury to the developing child, the highest burden in the youngest male workers is especially alarming. However, although the burden in women expressed in DALYs is distinctly lower than that in men, their burden might have a higher weighting when considering possible co-exposure of the unborn or breastfed children.

An overall EBD of 95,400 DALYs (8 DALYs/1,000 population) was estimated to be caused by chronic mercury intoxication due to occupational exposure to mercury in gold mining in Zimbabwe in 2004. This result was based on an assumed population of 350,000 gold miners in Zimbabwe in 2004. The latest estimate assumes a current number of 509,000 gold miners in Zimbabwe (Seccatore et al. 2014).

Integrating the DALY estimates into the top 20 causes of the BoD in Zimbabwe in 2004, estimated from a total of 132 disease and injury categories quantified by the WHO in the GBD 2004 update (WHO 2008b), chronic mercury intoxication due to ASGM would rank 13th (scenario range: rank 7 to 16; Table 8). Less than 2 DALYs/1,000 population in Zimbabwe in 2004 could be attributed to alcohol use disorders (WHO 2008b). In this analysis, severity of alcohol use disorders (in form of the DW) was assumed to be comparable to chronic mercury intoxication. Considering the general (aggregated) categories of disease and injury in the GBD classification system, the DALYs in the main analysis of chronic mercury intoxication are as high as those caused by malignant neoplasms in Zimbabwe in 2004 (WHO 2008b). Seen globally, the estimated rate of the burden of chronic mercury intoxication in Zimbabwe (DALYs/1,000) is comparable to the estimated worldwide rate of the burden from cerebrovascular disease (WHO 2008b).

The burden of all 132 diseases and injuries in Zimbabwe in 2004 as determined by the GBD (WHO 2008b, 2009) resulted in 680 DALYs/1,000 population. The estimated DALYs attributable to chronic mercury intoxication cover 1% of the total DALYs. By comparison, 1% of the global BoD is estimated to be attributable to lead-induced effects, if loss of IQ points, anemia, gastrointestinal symptoms in children, and cardiovascular diseases in adults were considered (Fewtrell et al. 2003).

Table 8: Integration of the DALYs due to chronic mercury intoxication (Steckling et al. 2014a) into the top 20 causes of burden of disease (BoD) for Zimbabwe in 2004 (WHO 2008b)

Ranking	Disease or injury*	Estimated DALYs** (per 1,000 population)
1	HIV/AIDS	385
2	Lower respiratory infections	21
3	Diarrheal diseases	18
4	Tuberculosis	16
5	Maternal conditions	13
6	Prematurity and low birth weight	13
Chronic mercury intoxication from occupational use of mercury in gold mining (scenario with the highest estimate)		12
7	Birth asphyxia and birth trauma	12
8	Road traffic accidents	12
9	Violence	11
10	Other unintentional injuries	11
11	Neonatal infections and other conditions	10
12	Protein-energy malnutrition	10
Chronic mercury intoxication from occupational use of mercury in gold mining (main analysis)		8
13	Congenital anomalies	7
14	Unipolar depressive disorders	6
15	Cerebrovascular disease	6
Chronic mercury intoxication from occupational use of mercury in gold mining (scenario with the lowest estimate)		6
16	Cataracts	5
17	Malaria	5
18	Ischemic heart disease	5
19	Meningitis	5
20	Asthma	4
Total DALYs of all 132 categories in the GBD 2004 study (WHO 2009)		680
Abbreviations: DALYs: disability-adjusted life years		
Explanation of symbols: * Chronic mercury intoxication is ranked amongst 132 categories of disease and injury. Unlike the 136 categories of disease and injury published in the GBD 2004 update (WHO 2008b) the GBD online database of the results for Zimbabwe (WHO 2009) does not divide "maternal conditions" into subcategories. General categories like neuropsychiatric conditions, cardiovascular diseases or malignant neoplasms are not listed. ** DALYs are rounded. Ranking is done by exact decimal place.		
Further explanations: For scenario analyses see P3 (Steckling et al. 2014a)		

While estimation of national DALYs lost due to use of mercury in ASGM has not been investigated before, other DALY quantifications with focus on mercury are available. For renal toxicity, a total of 83 DALYs (comprising just YLDs and no YLLs) was quantified for a population of 2,122,200 exposed to inorganic mercury at toxic waste sites (including mining regions) in India, Indonesia, and the Philippines (Chatham-Stephens et al. 2013). Another analysis focused on mild mental retardation (MMR) from exposure to methylmercury in different subgroups. The highest estimated burden was seen in Brazilian fishing communities located near gold mining regions with 203 DALYs per 1,000 infants. A burden of 46 DALYs/1,000 infants was estimated for a fishing village in Columbia, also located near gold mining activities. A Canadian subgroup of sport fishermen showed a burden of 7 DALYs/1,000 infants

(Poulin and Gibb 2008), which is comparable to the 8 DALYs/1,000 population (albeit not infants) due to chronic mercury intoxication in Zimbabwe (P3).

In the latest report on the world's worst pollution problems, Pure Earth estimated that at least 10 million of the global population is exposed to mercury from gold mining. A total disease burden of 1.5 million DALYs is assumed. However, this is a surrogate DALY value made on the assumption that the burden of moderately contaminated lead sites is equivalent to the burden of heavily contaminated mercury sites. The missing DW for health effects from elemental mercury allowed no DALY quantification on the basis of exposure to mercury (Pure Earth and Green Cross Switzerland 2015). Besides P3, where the scenario analyses of the preliminary DALY estimate identified the DW as the most sensitive factor, the report from Pure Earth is another source highlighting the need to determine the DW for the intoxication of elemental mercury exposure used in ASGM. Thus, P4 provides first evidence towards closing this research gap.

The key finding of P4 for subquestion III is that the HRQoL of CMMVI cases can be substantially reduced due to a broad range of health symptoms of varying severity caused by exposure to mercury used in ASGM (P4). While the diagnostic algorithm used in P3 considers exposure to any form of mercury and a measurable selection of associated health effects to identify cases of chronic intoxication (P3), P4 narrowed the focus on chronic exposures to metallic mercury vapor, these being the main route of exposure in ASGM. In addition, the disease profiles thus developed were limited to health symptoms of adults, while children were excluded. The susceptibility of children differs from that of adults given that children are still growing and developing (Sly and Pronczuk 2007, WHO 2006) and so needs to be examined separately. Regarding P1, there is an urgent research need. Descriptions must be precise when striving to derive DWs on the basis of the disease profiles developed. Co-exposures and co-morbidities need to be considered at a later step of the analysis. For example, within the GBD study, comorbidities were not included in the disease descriptions but considered when deriving DWs (Salomon et al. 2012).

To date, the HRQoL of ASG miners exposed to mercury has not been investigated. Comparing the EQ-5D+C-3L codes assigned with previous assessments for other diseases reveals that the HRQoL of a severe CMMVI (P4) was assessed in a manner similar to the HRQoL of schizophrenia (stage: several psychotic episodes, severe and increasing permanent) in a Dutch study (Stouthard et al. 1997). The dimensions self-care, pain, anxiety, and cognition of moderate CMMVI were assessed (P4) comparable to Parkinson's disease in the aforementioned

study. However, the dimensions mobility and usual daily activities are rated as more restricted in Parkinson's disease (Stouthard et al. 1997) than in moderate CMMVI (P4).

P4 has arisen from a research need identified in P3 and yields first evidence to determine the disease severity of mercury intoxication. The disease profiles developed in P4 form the basis to fill the gaps for an improved estimation of the EBD from the use of mercury in ASGM. P5 is based on all previous papers and aims at reducing the health risk by stopping the anthropogenic mercury emission from ASGM.

The following key finding delivers evidence to answer subquestion IV, *how to reduce the health risk from the use of mercury in ASGM*. As successfully tested in several countries (e.g., Appel and Jönsson (2010); compare list of countries and references in Chapter 2), the mercury-free gold extraction procedure using borax was found to be feasible for ASGM in Kadoma, Zimbabwe (P5). However, introducing it on a sustainable basis would require further measures. The procedure needs to be optimized according to the needs of the mining region by carefully considering of the subgroups affected (e.g., miners, millers).

Nevertheless, reducing mercury in ASGM is a challenge (Schmidt 2012). Aside from the mercury-free gold extraction procedure tested using borax, there is a wide range of other interventions (UNEP 2012, Zolnikov 2012). In order to introduce procedures to lower mercury emissions, the alternative options must be attractive to the miners to replace their established amalgamation procedure (Appel and Jönsson 2010, Styles et al. 2010). In contrast to mercury-free procedures, mercury-reducing procedures like fume hoods or retorts were tested. Retorts can catch up to 95% of the vaporized mercury during amalgam smelting; however, miners do not use such tools (Bosse Jönsson et al. 2013, UNEP 2012). Considering the answers of the questionnaire applied in the survey in Zimbabwe, only 11 miners (6%) used retorts (P3).

Zolnikov (2012) recently gave an overview of approaches for reducing exposure to mercury from ASGM, such as education programs, mercury-reducing and mercury-free methods, and awareness campaigns. UNEP published a practical guide and classified methods for mining and concentration, processing, and refining as poor, better, or best (UNEP 2012). However, no single solution was found which could be applied to every ASGM community. Methods need to be flexible so that every ASGM location can find its own appropriate solution (UNEP 2012, Zolnikov 2012). Starting from the considerable risk from mercury as described in this thesis (P1, P2, P3, P4), mercury-free measures should definitely be preferred to mercury-reducing measures.

By introducing an intervention to reduce the health risk from exposure to mercury used in ASGM, the intended risk reduction needs to be monitored to confirm its success. This can be done by using measures, like the analysis of mercury in human specimens (P2, P3), health examinations (P3), and EBD estimation (P3).

The mercury-free procedure tested might be one possibility to reduce the health burden from mercury in ASGM. However, even if wide-scale introduction is successful and further mercury emissions can be stopped, human health will still be at risk from the mercury already present in the environment. Returning to the no-exposure level will take centuries (Kessler 2013). The ongoing threat to mercury, even when applying a mercury-free procedure, was obvious on a small-scale during the project. Although the mill was cleaned before and no mercury was added during the testing, small particles were still found during ore concentration (P5). Consequently, reducing the 95,400 DALYs due to the use of mercury in ASGM (P3) might be possible if a comprehensive introduction of a mercury-free extraction process is possible, although there will be a remaining risk in the long term due to the contaminated environment.

This thesis contains results which can be used for human health risk analyses. Risk analyses are used to control situations where an exposure of populations to a hazard is possible (WHO 2004). The WHO's human health risk assessment toolkit for chemical hazards (WHO 2010b) was used as a guideline to demonstrate the research gaps filled by this thesis in a risk analysis framework. Table 9 shows the components¹⁸ of risk analyses. The consecutive steps *describe the risk* and *reduce the risk*, like formulated in the main research question of this thesis, are fundamental steps of risk analyses.

The available data was compiled and combined for this thesis and empirical findings gained by using materials and methods used commonly (e.g., HBM, health data), less commonly (e.g., diagnosing cases of chronic mercury intoxication) or which had not been used yet (e.g., DALYs, HRQoL) to describe exposure to mercury from ASGM. Results were obtained which can be integrated into 8 of the 9 steps of risk analysis (Table 9). Monitoring is the only step for which this thesis does not provide any evidence. This thesis contains results ranging from general to country-specific and even sample-specific levels. In the future, specific risk analyses with well-defined foci, e.g., like risk analyses of the use of mercury in specific ASGM regions, are recommended. Also, measures used in this thesis to describe the risk should be applied in a health impact assessment (HIA) to monitor a comprehensive introduction of a mercury-free extraction procedure.

¹⁸ Detailed explanations of the components of risk analyses are given in WHO (2004) and WHO (2010b).

Table 9: Components of risk analysis according to WHO (2004) and WHO (2000) and integration of this thesis

	Component	Step	Integration of this thesis in the risk analysis framework
Risk analysis	Risk assessment	Problem formulation	Summary of evidence about the health risk of the use of mercury in ASGM (P1, P2, P3, P4, P5)
		Hazard identification	Literature reviews regarding health effects (P1, P4); disease profiles including list of symptoms (P4)
		Hazard characterization	Using HBM values (HBM I and II) to characterize HBM data (P2, 3)
		Exposure assessment	HBM analyses of samples in Mongolia and Zimbabwe (P2, 3); literature review regarding children's exposure to mercury (in ASGM) (P1) and regarding exposure distribution of ASGM in Zimbabwe (P3)
		Risk characterization	Comparison of HBM data with the German HBM values (P2, P3); analyses of health data and determination of sample prevalence and extrapolation to the population in Zimbabwe; quantification of DALYs (P3); Summarizing evidence about the probability of occurrence of symptoms; HRQoL of health effects (P4)
	Risk management	Risk evaluation	Estimation of avoidable DALYs (P3)
		Emission and exposure control	Testing of a mercury-free extraction method to reduce emission and exposure (P5)
		Risk monitoring	/
	Risk communication	Information exchange	Publication of findings in peer reviewed journals (P1, P2, P3, P4, P5); theoretical workshop for gold miners and other stakeholders about risks of mercury and the need for a mercury-free extraction method (P5)
	Further explanations: The terms <i>hazard</i> and <i>risk</i> needs to be distinguished. Risk is defined as “the probability of an adverse effect in an organism, system, or (sub)population caused under specified circumstances by exposure to an agent”. Hazard is defined as “inherent property of an agent or situation having the potential to cause adverse effects when an organism, system, or (sub)population is exposed to that agent” (WHO 2010b, p. 12f).		

This thesis is limited by the following factors. Existing evidence included in all five papers (P1, P2, P3, P4, P5) was carefully reviewed but limited to the search strategy and search terms applied. Important information might have gone undiscovered as literature written in languages other than English or German was excluded. The primary data analyzed were limited by small sample sizes (P2, P3). However, given that ASGM is very informal or even illegal, every participant who provided samples and took part in an examination was very valuable. Due to data scarcity it was necessary to include assumptions and to model data for the preliminary DALY estimates (P3). A very limited number of experts were consulted as proxies to assess the HRQoL rather than asking intoxicated miners themselves (P4). The testing of a mercury-free extraction procedure was limited to a short field-based demonstration, which was realized by the use of simple methods (observations, discussions, and trial and error; P5). Detailed information about limiting factors is given in the respective papers.

This thesis addresses several research needs as identified in Chapter 2. In future studies, the ASGM regions with the highest mercury consumption should be addressed first in more detail in accordance with all steps of a human health risk analysis (Table 9). The main goal is to

reduce – and eventually completely eliminate the human health risk emanating from the use of mercury in ASGM.

7 Conclusions

The risk to human health of mercury used in ASGM is *considerable, subgroup-specific, and reducible*. Different materials and methods were used, and some methods had not been applied to this topic before, such as estimating the EBD and assessment of the HRQoL. Existing and newly collected materials were analyzed and combined to yield new evidence representing findings for 8 of 9 steps in a human health risk analysis framework.

After an assessment of the current state of research (Chapter 2), the following gaps were addressed in this thesis. The available evidence about mercury exposure and children's health were summarized (P1) to take account of this particularly vulnerable subgroup at risk to mercury. Next, HBM data from female miners and residents of child-bearing age in Mongolia not involved in mining but living in mining areas (P2) and male, female, and child miners in Zimbabwe (P3) was analyzed. Additionally, it was possible to present health data from the sample in Zimbabwe and to collect further data to estimate DALYs attributable to the use of mercury in ASGM in Zimbabwe (P3). Next, disease profiles suitable for DW derivations were developed including an extensive review of health symptoms due to chronic exposures to elemental mercury vapor and an assessment of the associated HRQoL (P4). Finally, inspired by the considerable human health risk due to the use of mercury in ASGM that was demonstrated, the feasibility of a mercury-free gold extraction method using borax was successfully tested in Zimbabwe (P5).

In the context of this thesis, the relevance of different subgroups for describing and reducing the mercury burden in ASGM was examined. Some subgroups warrant special attention either because of their particularly high vulnerability (fetuses and children), their influence on the exposure of others (e.g., pregnant women), or because of their particularly high EBD (young male gold miners).

As indicated in the background section, the necessity of describing and reducing the human health risk is concretized in the Minamata Convention on Mercury. The results of this thesis support the intention and underline the necessity of the Convention. It demonstrates the imperative of combatting an ongoing human health threat due to the use of mercury in ASGM. This thesis should be understood as an impetus to find solutions to protect human health against the dangers of mercury used in ASGM.

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Declaration of originality

I herewith certify that the work presented is the result of my own independent investigation. Wherever the work is indebted to the work of others, it has been acknowledged and cited. This thesis has not been accepted in substance for any other degree, nor is it concurrently being submitted in candidature or achievement of any other degree at any other university. I further declare that I have not previously made attempts to do a doctorate at any national or international university.

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