The role of qualitative risk assessment in environmental management: A Kazakhstani case study

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Abstract

Successful environmental management is partly contingent on the effective recognition and communication of environmental health risks to the public. Yet risk perceptions are known to differ between experts and laypeople; laypeople often exhibit higher perceptions of risk in comparison to experts, particularly when these risks are associated with radiation, nuclear power, or nuclear waste. This paper consequently explores stakeholder risk perceptions associated with a mercury-contaminated chloralkali production facility in Kazakhstan. Using field observations and in-depth interviews conducted in the vicinity of the Pavlodar Chemical Plant, this work assesses the relevance of the substantial on-site mercury contamination to the health and livelihoods of the local population with the goal of informing remediation activity through a combination of quantitative and qualitative risk assessments. The findings of this research study cannot be broadly generalized to all the primary stakeholders of the site due to the small sample size; however, the indifference of the local population towards both the possibility of mercury-related health risks and the need for mitigation activity could pose a substantial barrier to successful site remediation and also suggests that a qualitative understanding of stakeholder risk perceptions could play an important role in striving towards sustainable, long-term environmental risk management.

Key words

Risk perception; Kazakhstan; mercury; environmental health; risk assessment; remediation; environmental risk management

1.0 Introduction

Risk assessments are derived from the closely entwined concepts of *risk*[1] and *hazard*[2], and typically describe the potential adverse effects of exposure to hazards. In this context, however, it is necessary to distinguish between *external risks*, or the risks associated with events that may strike unexpectedly but with sufficient regularity within a population as to be predictable and insurable, and *manufactured risks,* which are instead created by the progression of science and technology and are therefore both incalculable and unpredictable (Giddens, 1999).

When considering how societies, organizations, or individuals should manage risk activities with unknown consequences, quantitative risk assessments are often endorsed as providing both a logical and systematic procedure for improving consequence-driven decision-making (Cox Jr., 2009). Complex environmental problems are however often based on manufactured risks and can therefore be challenging to address with traditional scientific procedures as existing knowledge bases are typically characterized by imperfect understanding of the various systems involved (van der Sluijs, 2006). In addition, by their very nature, risk assessments based on calculated risks tend to be inadequate for communication to the general population; public views of risk criteria tend to be more qualitative than quantitative (Covello, 1985) and as a result often diverge from those identified by a traditional risk assessment.

Societal risk perceptions have been described by Weinstein (1980) as a reflection of the values, symbols, ideology and history of a society (Weinstein, 1980); Sjöberg *et al.* further imply that risk perception is a social and cultural construct and that "the conflict between expert and public risk perception is at the basis of the social

[1] "The quantification of a hazard in terms of the probability that harm or undesirable effects will be realized" Baker F. Risk Communication about Environmental Hazards. Journal of Public Health Policy 1990; 11: 341-359..

[2] "An act or phenomenon posing potential harm to some person(s) or thing(s)" NRC. Improving Risk Communication. Washington, D.C.: National Academy Press, 1989..

dilemmas of risk management" (Sjöberg et al., 2004). An additional confounding factor is that risk perceptions can vary when comparing different groups of people, with many studies indicating that laypeople perceive risks and model risk decisions differently than technical experts. Therefore, in order to evaluate the potential differences between quantitatively derived and qualitatively perceived risk criteria, this research study focuses specifically on the environmental and human health risks associated with a mercury-contaminated industrial site in Kazakhstan, the Pavlodar Chemical Plant (PCP).

Previous risk assessments of the PCP site by Woodruff and Dack (2004) and Ullrich *et al.* (2007) evaluated human health risks and accounted for social and economic aspects primarily through quantitative factors (Ullrich et al., 2007a; Ullrich et al., 2007b; Woodruff and Dack, 2004); these assessments have been further substantiated by ongoing groundwater, soil, and air quality monitoring by Kazakhstani researchers. Given the weaknesses of such an exclusively quantitative risk assessment in effective environmental risk management and site remediation, this work aimed to explore whether a risk assessment framework that integrated qualitative components could allow for more optimized environmental risk management through the selection of remediation solutions that are both technically sound and sustainable in the long-term due to stakeholder engagement.

More specifically, the primary objectives of this study were to:

1) Understand the risk perceptions of primary stakeholders associated with the Khimprom Plant in order to facilitate risk management dialogue;
2) Evaluate the relevance of the environmental and human health risks associated with site contamination within the context of broader societal risks while aiming to identify the salient risks to the population; and
3) Assess the potential implications of stakeholder risk perceptions on risk management, isolating possible barriers to the implementation of a successful remediation solution.

However, given the fluid nature of environmental contamination and the fact that the quantitative risk assessments by Woodruff and Dack and Ullrich *et al*. relied on data from 2001 and 2002, a smaller quantitative component of our study aimed to characterize the spatial and temporal variation in total mercury concentrations across the length of the plume in the fall of 2007 (when the qualitative research was conducted). In addition, we present the most recent measurements of total mercury concentrations in air, soil and groundwater collected by the Kazakhstani research team between 2004-2008, in order to more accurately compare and contrast perceived risk against quantitatively established mercury health risks.

In conducting this research, we first provide further background on the human health risks and recommended exposure limits associated with mercury, the use of mercury within the chloralkali industry, and the history of the Pavlodar Chemical Plant (PCP), before summarizing the results of existing quantitative risk assessments and more recent monitoring data from the Pavlodar site. We then examine the differences between quantitative and perceived environmental and human health risks associated with the site contamination based on semi-structured interviews of primary stakeholders. Finally, based on this analysis, we discuss the potential implications of this research study for developing sustainable, long-term environmental risk management solutions.

1.1 Mercury health risks

Mercury is toxic to humans in both inorganic and organic (e.g. methylated) forms (Hutchison and Atwood, 2003), but the absorption, distribution, metabolism, and excretion of mercury are highly compound-specific (Appendix A, Table A.1). Based on the potential for adverse health effects, the recommended environmental and occupational exposure limits for mercury are summarized (Table 1).

Table 1: Environmental and occupational exposure limits for mercury

Defined limit	Delegating body	Threshold exposure limit
Air exposure	OSHA	0.1 mg Hg/m^3 over 8 hours (elemental) 0.05 mg Hg/m^3 over 8 hours (organic)
Ambient air criteria	Clean Air Act (EPA)	0.00006 mg Hg/m^3 air
Drinking water exposure	EPA	≤ 2 μg/L
Ambient water quality criteria	Clean Water Act (EPA)	144 ng/L
Total body burden		20-30 mg
Oral reference dose	EPA	≤ 0.01 μg/kg body weight
Fish tissue residue criterion	EPA	0.3 mg MeHg/kg fish

OSHA – Occupational Safety and Health Commission
NIOSH – National Institute for Occupational Safety and Health
EPA – Environmental Protection Agency
FDA – Food and Drug Administration
MeHg – methyl mercury

Modified from (Broussard et al., 2002; Ullrich et al., 2007b)

Methyl mercury compounds pose the greatest risk to human health as they are extensively absorbed through the GI tract (Keating et al., 1997) and primarily target the central nervous system (Clarkson and Magos, 2006). However, although adverse neurological effects due to long-term methyl mercury exposure are irreversible, there is limited evidence of the direct impact of methyl mercury exposure through a fish-based diet (Clarkson and Magos, 2006; Wheatley and Wheatley, 2000) and mild or transient effects may not justify advice which will affect the lifestyle and ultimate health of populations for whom fish and wildlife are a vital component of diet, culture, and socio-economic well-being (Wheatley and Wheatley, 2000). Addressing such complex contamination issues requires a holistic approach that encompasses social and economic impacts rather than relying on technical knowledge alone.

1.2 The chlor-alkali industry

Chlorine and caustic soda (NaOH) are most commonly manufactured through one of three electrolytic processes (diaphragm, membrane, and mercury cell, respectively) in which the electrolysis of a salt solution converts chloride ions to elemental chlorine (Appendix A, Table A.2) (The Chlorine Institute Inc., 2008). Most chlorine production processes in North America utilize diaphragm cell technology, however, the use of mercury-cell electrolysis, particularly in less developed countries where stringent environmental regulations are lacking and/or inadequately enforced, has made a significant contribution to anthropogenic mercury emissions (European

Commission, 2008). Further, the decommissioning of older facilities with the goal of transitioning to cleaner production processes has resulted in a number of heavily contaminated industrial sites (*e.g.*, the Pavlodar Chemical Plant) that threaten ecological security (Lodenius and Tulisalo, 1984; Ullrich et al., 2007a).

1.3 The Pavlodar Chemical Plant (PCP)

The Pavlodar Chemical Plant (formally known as Khimprom) was designed as a dual-purpose production facility capable of manufacturing both civilian chemicals and agents of chemical warfare (Bozheyeva, 2000) and constructed between 1965 and 1992 in the northern industrial zone of the Kazakhstani city of Pavlodar (Ilyushchenko et al., 2007), a major industrial centre with a population of over 300,000 people that also contains other chemical plants, an oil refinery, and several power stations (Ullrich et al., 2007a). The Plant itself is located on a semi-consolidated sand aquifer, primarily comprised of coarse and medium-grained sand, with limited quantities of fine-grained sand and clay and with a relatively shallow groundwater table located <10 meters below the surface (Ilyushchenko et al., 2007).

The civilian chemical production site at the Pavlodar Plant included a chloralkali production facility that utilized mercury-cell electrolysis to produce chlorine and caustic soda (Ilyushchenko et al., 2007). Unfortunately, total mercury losses to the environment during plant operations between 1975 and 1993 have been estimated at ~1,000 tonnes through both atmospheric mercury emissions and the seepage of elemental mercury into the soil and groundwater (Ullrich et al., 2007a). Industrial and domestic wastewater from the Plant was discharged to Lake Balkyldak, an artificial storage pond formed from a natural depression north of the Plant (Fig. 1b). However, the ineffective operation of the wastewater treatment plant at the chloralkali factory – used to treat the deionized water used to strip sodium hydroxide from the mercury cathode – is thought to have resulted in the majority of the mercury in the wastewater (estimated at 15-40 mg/L total Hg) entering the lake (Ullrich et al., 2007a).

Production of chlorine and caustic soda at the plant was terminated in 1993 and the chloralkali workshop was completely dismantled, with the majority of debris and contaminated soil consigned to an on-site landfill lined with 0.5 m of clay and 2.5 m of cement, and capped with both clay and asphalt (Ilyushchenko et al., 2007). However, as of 2011, the Plant has once again commenced production of chlorine and caustic soda following a transition to membrane-based electrolysis (Ilyushchenko, 2011b).

2.0 Materials and Methods

This study is based on a combination of field observations and in-depth interviews conducted with the primary stakeholders associated with the Pavlodar Chemical Plant (PCP) in September 2007. The quantitative component of this research aimed to supplement existing data (Ilyushchenko, 2006; Ullrich et al., 2007a; Ullrich et al., 2007b; Woodruff and Dack, 2004) by providing more recent measures of the on-site mercury contamination and allowing for a more accurate qualitative exploration of the differences between local perceptions of mercury health risks and the quantitative risks established by previous risk assessments and site monitoring.

2.1 Quantitative Risk Assessment

When conducting field sampling at the PCP site in September 2007, a combination of personal judgment and stratified random sampling methods were applied. Thirteen sampling locations were chosen in total with the aim of providing a comprehensive representation of the spatial variation in mercury concentrations extending across the length of the plume from the point source of contamination and also allowing for the estimation of background concentrations of mercury in groundwater (Fig. 1). These measurements were taken in conjunction with the Kazakhstani research team (based at the Almaty Institute of Power Engineering and Telecommunications, AIPET) responsible for monitoring soil and groundwater contamination at the PCP site (Ilyushchenko, 2011a).

The groundwater sampling and analytical procedures used by the Kazakhstani research team have previously been summarized (Ilyushchenko, 2006; Ilyushchenko, 2011a); however, at each sampled well, an additional 500 mL groundwater sample was collected for total Hg analysis using cold-vapour atomic absorption spectrometry by the Oxford research team. These samples were collected and filtered using a 0.2 μm membrane filter (Whatman Ltd., UK) before preservation with $K_2Cr_2O_7$ and HNO_3 (1 g/L and 76.1 g/L, respectively) (Yu and Yang, 2003) and storage in dark glass bottles with polytetrafluoroethylene- (PTFE-) lined caps at 4°C . Additional measurements taken at each well included pH, redox potential (Eh) and groundwater temperature.

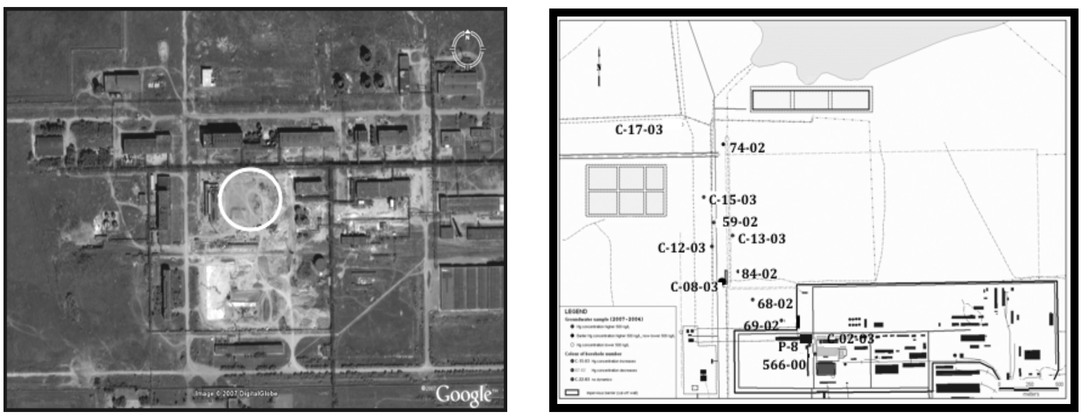

FIGURE 1: **a) Satellite image of the Khimprom Plant, showing the former location of the electrolysis factory** (Google Earth, 2007)
b) A site map of the Khimprom Plant illustrating the groundwater monitoring wells sampled in September 2007 (Ilyushchenko, 2006)

Prior to analysis for total Hg in Oxford, each sample was serially diluted in a 5 mL solution of $K_2Cr_2O_7$ and HNO_3 (1 g/L and 76.1 g/L, respectively) to an Hg(II) concentration between 0.5 and 100 ng/L. Total Hg was measured using a RA-915+ atomic absorption spectrometer with a RP-91 cold-vapor attachment (OhioLumex Co.). All liquid samples were analyzed in triplicate; for each 5 mL sample, 2 mL of $SnCl_2$ reducing solution (100 g/L $SnCl_2 \cdot 2H_2O$ in 35% sulphuric acid) was added to release atomic mercury in gaseous form, which was conveyed to the analytical cell at an airflow rate of 4 L/min. The detection limit for total Hg was 0.5 ng/L.

2.2 Qualitative Risk Assessment

The qualitative component of this study is based on a total of seventeen semi-structured in-depth interviews conducted with three different stakeholder groups associated with the Pavlodar Chemical Plant:

1) Kazakhstani scientists involved in site remediation and monitoring
2) Site workers at the Khimprom Plant
3) Villagers from Pavlodarskye, a village located 3 km west of the Plant

These three categories were chosen as they encompassed all of the primary stakeholders of the Khimprom site (with the exception of local government authorities) as well as those population groups likely to experience significant health risks due to the on-site mercury contamination. Rather than comparing all individuals associated with the site as a single sample group, and given that the interviewees had varying backgrounds with respect to education, employment, sex and family status, the three categories were used to differentiate interview respondents based on their frames of reference associated with the site and achieve more accurate analysis. Local government ministers of Pavlodar *oblast* were originally included as a fourth sample group; however, all requests for interviews or comments were declined on the basis that Kazakhstani government officials could not be interviewed by foreigners. Unfortunately, this deficit made it impossible to isolate potential policy barriers (*i.e.*, the lack of support of the state government) and their implications for the successful remediation of the site.

Recruitment strategies also varied for each of the three categories of respondents. Two of the four scientists interviewed were based in the former Kazakhstani capital of Almaty and were known to the interviewer through their association with the quantitative site-monitoring program. The other two scientists were based in Pavlodar and were recruited by the Almaty scientists. Site workers, with the exception of the site manager, were recruited by word-of-mouth while interviews were taking place. Local villagers in Pavlodarskye were interviewed door-to-door with the assistance of one of the Pavlodar-based scientists who was a Pavlodarskye resident; these interviews would not have been possible without this local contact. In conducting this work, semi-structured interviews were used as they allow for research that is responsive to the experiences of the respondents with relation to the subject matter, and encourages them to relate to questions on their own terms, based on their own frames of reference (Walker, 1985). Semi-structured (unlike structured) interviews also allow for misconceptions and/or interesting ideas to be followed up immediately, leading to the exploration of relevant topics that may previously have been disregarded. As a gesture of respect to Kazakhstani culture, these interviews were not recorded, although detailed notes were taken and later transcribed. As the interviewer lacked fluency in Russian (an official language of Kazakhstan), all interviews used a Russian-English translator. The majority of interviews were thirty minutes in length, but ranged overall from twenty to sixty minutes. In total, four scientists, seven site workers (including the site manager) and seven villagers were interviewed, ranging in age from early twenties to late fifties.

The interview questions (Appendix B, Tables B.1-B.3) covered the respondents' overall knowledge of the mercury spill and perceptions of personal risk associated with the contamination, but varied slightly for each category of respondents based on their anticipated knowledge of the site and frames of reference. All of the respondents were questioned on their understanding of mercury and mercury-related health risks; on which parties they believed to be the most susceptible to health risks associated with the contamination; and on what they believed would be an ideal solution to the mercury contamination problem. The research scientists were asked more detailed questions regarding their motivations for becoming involved with remediation work at the Khimprom site, and what they believed would be the best possible remediation solution for the site based on their higher assumed level of scientific understanding (Appendix B).

In addition to the main interview questions, the Khimprom Plant workers were asked additional questions about their work experience at the plant, their average working hours, and about the availability of protective clothing and equipment when working in mercury-contaminated areas. Site workers were also questioned on whether they lived in close proximity to the Khimprom Plant (*i.e.* in Pavlodarskye) or commuted from the city of Pavlodar. The site manager, based on his additional knowledge of the mercury spill, was asked how long he believed it would take to achieve an adequate solution to the mercury contaminated, and also to share his thoughts on the best possible solution.

The proposed questions for the Pavlodarskye villagers originally anticipated a fairly simplistic understanding of groundwater mercury contamination. In practice however, the villagers were all well informed regarding the movement of contaminants through soil and groundwater and more complex questioning would also have been possible. The villagers were asked specific questions about their sources of food and drinking water, their locations for cattle grazing, and whether they used the same water sources for both irrigation and drinking water. Villagers were also asked whether they fished in Lake Balkyldak, a saline lake where fishing is illegal due to elevated mercury concentrations (Ilyushchenko et al., 2007) or in the River Irtysh, a large river which is the main water source for the City of Pavlodar.

Although all interviews should preferably have been conducted in the absence of any third parties, this was not always possible. The site manager and research scientists were interviewed in the sole presence of the interviewer and the Russian–English translator, but the site workers were interviewed in an open office where other staff members were occasionally present. Although some interview respondents may have tailored their answers in the presence of their co-workers, there were no other venues available to the interviewer. The villagers were interviewed in the presence of a translator and one of the interviewed scientists, a Pavlodarskye resident whose presence was necessary to connect with the local people and to encourage their participation. It is possible that there may have been some selection bias on the part of the local scientist, but villagers were not receptive to contact without the presence of a familiar face. As mentioned previously, the interviews in Pavlodarskye were conducted door-to-door, in front of each dwelling.

Prior to each interview, all respondents were informed about the purpose of the interview, that their participation was voluntary and that they were not obliged to answer all questions and could ask for clarification, pause, or stop the interview at any time. All participants (with the exception of the Khimprom Plant site manager and Almaty-based scientists who are known internationally due to their association with the Khimprom site) were promised anonymity.

The interview data was analyzed through two sequential phases: data immersion and data processing (Miles and Huberman, 1994). During the data immersion phase, the author reviewed the interviews and field notes until she was highly familiar with the content and had identified emerging themes while recognizing that the size of the sample may not have been sufficient to identify all of the emergent issues. Evident themes were further dissected during the data processing phase, in which data was divided into different categories and across different sample groups, allowing for a summary of the key points and the incorporation of translated quotations.

3.0 Results and Discussion

3.1 Quantitative Risk Assessment

The results of the total mercury analysis in Oxford indicated total Hg concentrations of 0.088-131 μg/L within the mercury plume, with background concentrations of ~0.035 μg/L (Fig. 2a).

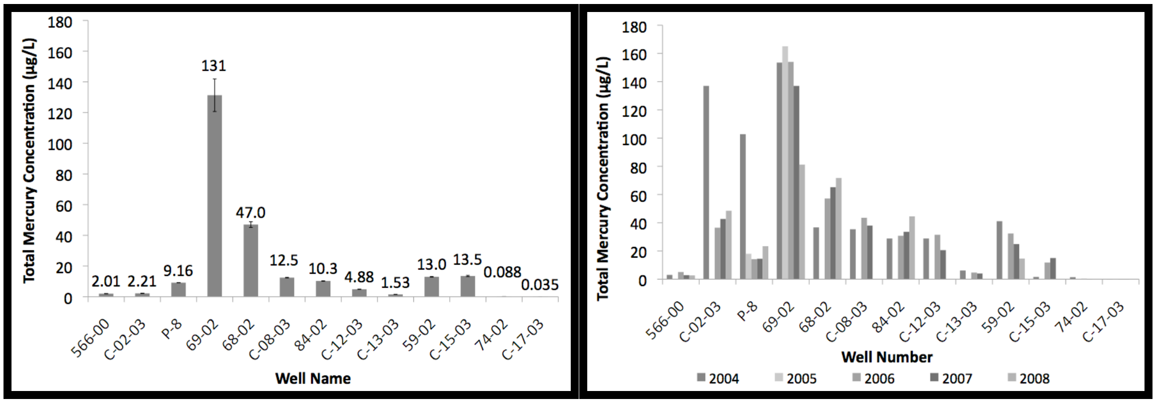

FIGURE 2: (a) Total Hg concentrations measured in Oxford from groundwater wells sampled at the Khimprom Plant in September 2007; error bars indicate the standard deviation of triplicate measurements. Well ordering follows the plume. (b) Total Hg concentrations measured at the Pavlodar Chemical Plant by Kazakhstani researchers between 2004 and 2008 (Ilyushchenko, 2011a)

The highest mercury concentrations measured by the Oxford research team were at Well 69-02, located approximately 300 meters northwest of the mercury landfill (Fig. 2a). This data substantiated measurements taken by the Kazakhstani research team from 2004-2008, which ranged from 0.0062-137 μg/L and are presented along with the most recent air and soil monitoring data (Table 2).

Table 2: Total Hg concentrations in air, soil and groundwater at the PCP site

Medium	Units	Year	No. Samples	Mean	Std. Deviation	Min.	Max.
Air	(mg/m^3)	2006	16	1.43	4.07	0.082	16.63
Soil	(mg/kg)	2006	19	nd	nd	2.1	95.1
Groundwater	(μg/L)	2007	83	10.7	23.0	0.0062	137

Modified from (Ilyushchenko, 2006)

Based on the data presented (Table 2), the mean air concentration of total mercury at the PCP site is more than ten times the threshold exposure limit recommended by the U.S. Occupational Health and Safety Commission (OSHA) (Table 1), suggesting that the continued operation of the PCP site as an industrial facility could pose a significant risk to site workers. Further, the mean groundwater concentration at the PCP site, based on the measurements of the Kazakhstani research team, was not only more than three orders of magnitude greater than the background concentration of 6.2 ng/L, but also almost two orders of magnitude greater than the U.S. EPA Clean Water Act ambient water quality criteria of 144 ng/L (Table 1).

As mentioned previously, earlier work by Woodruff and Dack quantified average daily exposures and toxic risks as hazard quotients to the local population from measurements of soil and groundwater contamination in the vicinity of Pavlodarskye (a village located three kilometres west of the Plant) using both the UK Contaminated Land Exposure Assessment (CLEA) Model and the Netherlands, Van Hall Institute Risc-Human Model Version 3.0 for Risk Assessment for Soil Contamination (Woodruff and Dack, 2004). Similarly, studies by Ullrich *et al.* evaluated total Hg concentrations in soils and groundwater from private gardens and drinking water wells in Pavlodarskye, in bovine milk and tissue in cows from Pavlodarskye grazed near the PCP site, and in the tissues of fish from both Lake Balkyldak and the River Irtysh, the two sources of fish for the population of Pavlodarskye (Table 3) (Ullrich et al., 2007b).

Table 3: Total Hg concentrations in soil and groundwater in Pavlodarskye and fish tissues from Lake Balkyldak

Medium	Units	Year	No. Samples	Mean	Std. Dev.	Min.	Max.
Soil	(mg/kg)	2001	24	1.04	nd	0.10	3.30
Groundwater	(ng/L)	2001	30	<5.0	nd	<5.0	<5.0
Fish - Balkyldak	(mg/kg)	2001	55	0.89	0.05	0.16	2.20
Fish - Irtysh	(mg/kg)	2001	30	0.112	0.004	0.075	0.159
Bovine milk	(μg/kg)	2001	15	<2.0	nd	<2.0	<2.0
Bovine kidney tissue	(μg/kg)	2001	1	10.96	10.1%*	-	-

*For bovine kidney tissue, the relative percentage difference (RPD) for duplicates is presented, rather than standard deviation.
nd – not determined; data unavailable

Summarized from (Ullrich et al., 2007b)

Based on the work of Ullrich *et al.*, the concentrations of mercury in the groundwater in Pavlodarskye were well below the detection limit of 5 ng/L and fully compliant with drinking water standards of the EU and WHO (1 μg/L) as well as Kazakhstani water standards (0.5 μg/L); therefore drinking water contamination does not pose a significant current health risk (Ullrich et al., 2007b). The fish collected from Lake Balkyldak, by contrast, were seriously contaminated by Hg, with 91% of fish exceeding the U.S. EPA fish tissue criterion of 0.3 mg MeHg/kg fish (Ullrich et al., 2007b). Therefore, the most significant route of potential mercury exposure to the population of Pavlodarskye is most likely through the consumption of fish from Lake Balkyldak, assuming that village residents do not visit or work at the PCP site (Ullrich et al., 2007b).

Ullrich *et al*. recommend further studies to determine the environmental and human health impacts associated with cattle grazing on contaminated land around the PCP site and drinking contaminated surface water (Ullrich et al., 2007b); however, measurements of mercury concentrations in the population of Pavlodarskye via blood, urine or hair samples may also be prudent in order to more accurately assess their Hg exposure.

3.2 Qualitative Risk Assessment

Stakeholder risk perceptions were first analyzed by exploring assessments of mercury-related environmental and human health risks by the scientists associated with the Khimprom field site. These scientists were assumed to have been well informed of existing air and groundwater monitoring results, the hydrological modeling of the mercury plume, and the existing quantitative risk assessments, due to their long-term (≥5 year) involvement with the Khimprom site. The responses of the scientists were compared and contrasted with existing risk assessments of the Khimprom site conducted by Woodruff *et al.* (Woodruff and Dack, 2004) and Ullrich *et al.* (2007) (Ullrich et al., 2007a; Ullrich et al., 2007b),

3.2.1 Scientists

All of the scientists interviewed affirmed their belief in mercury-related human health risks associated with the contamination at the Khimprom site; the primary perceived health risk was the inhalation of gaseous elemental mercury:

> *"The most dangerous thing about mercury is exposure to mercury vapors…the most dangerous thing about mercury contamination is that [the vapor] is invisible. The vegetation is dangerous, but people have no idea that inhaling the vapor is even more dangerous." (Pavlodar scientist)*

The majority of the scientists (3 out of 4 interviewees) also cited the need for more consistent monitoring of air quality at the PCP site in order to minimize the risk of exposure to site personnel. This is particularly given that the site is once again operating at full capacity (Ilyushchenko, 2011b).

3.2.2 Site Workers

The site workers, like the local scientists, were assumed to have been kept informed of on-site contamination and remediation efforts and were therefore thought to possess a comparable level of risk awareness. Unlike the scientists, however, site workers were expected to lack access to the existing risk assessments published in the literature and their perceptions of mercury health risks were consequently anticipated to represent innate environmental risk perceptions amongst the Kazakhstani people. Prior to conducting the interviews, it was also assumed that the site workers were less likely to have had post-graduate education and/or to fully appreciate quantitative measures of ecological risks.

The majority of the site workers interviewed had worked at the site for over twenty years. Despite their personal experience with mercury-related occupational diseases in their colleagues, the majority of interview respondents believed that the mercury contamination at the site was no longer a problem and emphasized their belief in the knowledge and integrity of the site management and the remediation scientists working at the Khimprom Plant:

> *"I assume that [mercury] exists, but not in large quantities. I do not feel personally affected by the mercury spill, and I do not think there is any risk to anyone else either. If the scientists feel that the containment is enough, then it is enough." (Khimprom Plant worker)*

This staunch belief corroborates with the theory proposed by Hance *et al.* (1998) that the public is more accepting of risks that can be explained by scientists than those about which scientists must admit a great deal of uncertainty (Hance et al., 1988). Based on this finding it is also possible that the propagation of implied scientific understanding through community dialogue and marketing could help streamline novel technology adoption by increasing public acceptance.

3.2.3 Pavlodarskye villagers

In contrast with the local scientists and the Khimprom Plant workers, the risk perception and understanding of the Pavlodarske villagers was anticipated to illustrate the effects of risk communication on overall risk awareness in stakeholders who had limited access to post-secondary education and quantitative risk data, although information regarding the mercury spill and its associated health risks had been propagated through a number of media outlets, including radio, television, and newspapers. However, both scientists based in Pavlodar referred to targeted education programs in Pavlodarskye regarding mercury health risk, including a trip to Lake Balkyldak for local school children. Also mentioned was the fact that a local NGO that was hoping to increase awareness in the community by raising funds to publish a booklet describing regional environmental problems.

As a result of these outreach measures, the villagers interviewed had surprisingly sophisticated understanding of groundwater contamination and mercury health risk. Even so, the villagers were overwhelmingly indifferent towards the problem:

> *"I know that mercury is a metal, and that it is hazardous. I know that there is a problem [with the mercury here], but it is not* ***our*** *problem. We have our own problems; therefore the mercury at the plant is not our concern. One issue is people selling fish at the village market that was caught at [contaminated] Lake Balkyldak." (Pavlodarskye villager)*

Concerns regarding the consumption of contaminated produce had been highlighted in the literature by Woodruff and Dack (Woodruff and Dack, 2004), although Ullrich *et al*. suggested that the greatest risk of mercury exposure to the local population was from the consumption of fish from Lake Balkyldak (Ullrich et al., 2007b). However, Woodruff *et al*. also emphasized that the social implications of not eating contaminated meat, fish, or produce were much more complex, and that any successful management plan to deal with on-site mercury contamination would require a comprehensive approach that accounted for the fact that when food is scarce, the only choice for the local people may be between eating mercury-contaminated goods or not eating at all (Woodruff and Dack, 2004).

When conducting the present study, the interviewer also noted that the majority of the local villagers were subsistence farmers whose diets were reliant on homegrown vegetables, raising livestock and fishing from the River Irtysh. Low wages also prompted some locals to engage in illegal fishing at Lake Balkyldak to supplement their diet and incomes. Therefore, emphasizing the health risks associated with consuming local meat, fish and produce could cause additional significant social, economic and health risks due to a lack of alternatives.

3.2.4 Key findings and implications for risk management

The key findings from each of the stakeholder groups are summarized (Table 4).

Table 4: Key findings of qualitative risk assessment

Stakeholder group	Primary perceived risk(s)	Recommendation(s)
Scientists	Inhalation of gaseous elemental mercury	More consistent air quality monitoring to assess risk
Site workers	None, all believed that the mercury contamination had been sufficiently contained and/or addressed	Continued monitoring to ensure the mercury remained contained
Pavlodarskye villagers	Groundwater/soil contamination Contaminated fish from Lake Balkyldak	None; belief that those who caused the contamination should fix it

As the scientists were the only stakeholder group assumed to be well-informed of existing site monitoring data, it was interesting that their perceptions of the primary mercury-associated health risk corroborated with the air quality risks established by the Kazakhstani researchers in 2006 (Ilyushchenko, 2006). By contrast, the site workers, despite having long tenures of employment at the site and sharing personal experiences of mercury-related occupational health diseases in their colleagues, shared an overwhelming belief that the mercury contamination was under control and the Pavlodarskye villagers were primarily concerned with the potential for groundwater contamination due to the migration of the mercury plume, although they also acknowledged the potential health risks associated with the consumption of fish from Lake Balkyldak.

Although the results of this study cannot be generalized to all of the primary stakeholders of the site due to the small sample size, the viewpoints of all of these groups suggest that knowledge dissemination and risk dialogue do have an impact on environmental risk perceptions, and that the risk perceptions of laypeople can and vary from quantitatively established risks. The perceptions of the scientists were consistent with their access to quantitative risk data that had highlighted the potential risks associated with gaseous elemental mercury, while the site workers appeared to be primarily influenced with the risk messaging that they received from the scientists and site management indicating that the mercury contamination was under control. Similarly, the fact that the Pavlodarskye villagers were primarily concerned with the potential for drinking water contamination could have been influenced by the fact that 20 private wells were tested for mercury contamination in 2001/2002, although the results of this work clearly indicated that drinking water exposure to mercury was not an issue (Ullrich et al., 2007b). The villagers' acknowledgement of the risks associated with the consumption of fish from Lake Balkyldak could also have been simply because of a series of information pamphlets that had been distributed throughout the community outlining these risks. The current work did not seek to evaluate whether the propagation of information through print media (McCallum et al., 1991) was sufficient to initiate behavioral change in the consumption patterns of Pavlodarskye residents and/or whether face-to-face communication with friends and neighbors and officials had a greater influence on risk behavior (Wakefield and Elliott, 2003) but this question could form the basis of a future qualitative research study.

Finally, despite their acknowledgement of potential mercury-related health risks, none of the stakeholder groups interviewed felt that further remediation action was necessary, although two out of three groups recommended continued and/or more extensive site monitoring. The sense of indifference towards addressing the contamination issue that was prevalent amongst the majority of stakeholder groups (but most evident amongst the Pavlodarskye villagers) could suggest that there are more significant social and economic problems within the community.

Therefore, this research study successfully implies that a qualitative understanding of stakeholder risk perceptions is a valuable component of a successful risk management strategy, although the preliminary findings of the current work must be substantiated through a larger and more comprehensive research study that further explores the connection between societal and environmental risk perceptions in the Kazakhstani population, However, the indifference towards local contamination issues by the majority of interview correspondents may suggest that the recent shift towards two-way communication processes in risk management (where public concern and public risk perception are criteria for risk regulation (Klinke and Renn, 2002)) is not currently practical for risk management in former Soviet states such as Kazakhstan.

Further, the contemporary approach to risk communication defined by Trettin and Musham (2000) as going beyond alerting or reassuring the public about potential environmental hazards and instead "stimulating interest in environmental health issues, increasing public knowledge, and involving citizens in decision making" (Trettin and Musham, 2000) would be challenging to apply in this context. Despite recognizing that they might ultimately suffer from health problems associated with the mercury contamination, the local population lacked the motivation to engage with the issue and believed that the problem needed to be solved by the original perpetrators. A Pavlodar scientist perhaps most clearly articulated the problem:

> *"The local population is indifferent. They do not care about this [mercury] problem and continue to fish in Lake Balkyldak. Most people feel unable to do anything about the problem – everything is decided at a higher level – so they don't care." (Pavlodar scientist)*

This statement supports earlier research highlighting systematic differences in response to health risks for those differing in ethnicity, socioeconomic status, and educational level (Vaughan, 1993) and also suggests that unless an effort is made to encourage the local population to take greater ownership of the contamination problem, they are unlikely to engage in effective, interactive risk communication (Renz, 1992). This indifference poses a considerable barrier to the successful risk management of this site and may well be both relevant and worth considering in other chronic mercury contamination situations, both in Kazakhstan and internationally (*e.g.,* the Santa Gilla lagoon, Sardinia; Onandaga Lake, New York State; and Lavaca Bay, Texas (Ullrich et al., 2007a)) as local risk perceptions can provide a powerful inducement to engage both foreign researchers and international organizations such as the World Bank in accelerating remediation efforts.

4.0 Conclusions

The qualitative analysis of mercury risk at the Khimprom site illustrated that the risk perceptions of laypeople can differ from quantitatively established human health risks, and also suggested that sustainable, long-term environmental risk management requires a nuanced understanding of stakeholder perceptions of environmental risk in addition to a comprehensive quantitative risk assessment. Although existing quantitative risk assessments and ongoing site monitoring identified the potential health risks associated with the continued presence of mercury at the Khimprom Site, the qualitative risk assessment illustrated the influence of the type and extent of knowledge dissemination on stakeholder risk perceptions. In addition, the qualitative risk assessment recognized that the general indifference of the local community to the mercury contamination could become a significant barrier to successful risk management, as a remediation solution cannot be maintained in the long-term without the interest and engagement of local stakeholders. A qualitative understanding of stakeholder perceptions could therefore help contribute towards a sustainable remediation solution that addresses ecological risks while simultaneously engaging the local population in implementation, monitoring and site management to ensure long-term success.

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APPENDIX A

Table A.1: Health effects of mercury compounds

Compound	Effects	Reference
Elemental (Hg^0)	- Poorly absorbed through the gastrointestinal (GI) tract - Primarily absorbed by inhalation in the gaseous form - 70 – 80% of inhaled mercury vapour is retained by the body - Tends to be sequestered in the kidneys and nervous system - Main symptoms are tremors and psychological disturbances - Urine and faeces are the primary excretion pathways although exhaled air, saliva, and sweat can also contain mercury	(Keating et al., 1997) (Schwenk et al., 2009) (Clarkson, 2002) (Clarkson and Magos, 2006) (Clarkson and Magos, 2006) (Clarkson and Magos, 2006) (Keating et al., 1997)
Inorganic (Hg^+, Hg^{2+})	- Exists in both mercurous and mercuric forms - Mercurous chloride has laxative properties, however little information is available on its distribution through the body - Water-soluble mercuric salts are potent poisons that can cause immense corrosive damage to the GI tract and result in the complete collapse of kidney function due to renal accumulation - Mercuric salts can also cause gastroenteritis and stomatitis - Primary pathway of excretion is through faeces	(Clarkson and Magos, 2006) (Magos and Clarkson, 2006) (Clarkson and Magos, 2006) (Clarkson and Magos, 2006) (Keating et al., 1997)
Methylated (CH_3Hg^+)	- Pose the greatest risk to human health - Are rapidly and extensively absorbed through the GI tract and primarily target the central nervous system - Bioaccumulates in all aquatic species due to the methylation of inorganic mercury by aquatic microorganisms - ~95% of methyl mercury ingested is absorbed through the GI tract and distributed throughout the body in 30 hours - Health effects include signs of incoordination, constricted visual fields, and numbness in the extremities	(Keating et al., 1997) (Clarkson and Magos, 2006) (Magos and Clarkson, 2006) (Clarkson, 2002) (Clarkson, 2002)

Table A.2: Electrolytic production processes for chlorine and caustic soda

Process	Description
Diaphragm cell	A nearly saturated sodium chloride solution is fed to the diaphragm cell anode compartment and flows through the diaphragm to the cathode section. Chloride ions are oxidized at the anode to produce chlorine gas, while hydrogen gas and hydroxide ions are produced at the cathode. The migration of sodium ions from the anode to the cathode produce cell liquor containing 10-12% sodium ydroxide; the migration of some chloride ions results in the cell liquor containing about 16% sodium chloride. An evaporation process concentrates the cell liquor to 50% sodium hydroxide while the recovered salt is returned to the brine system for reuse.
Membrane cell	Perfluorinated polymer ion exchange membranes are used to separate anodes and cathodes within the electrolyzer. Ultra-pure brine is fed to the anode compartments where chloride ions oxidize to form chlorine gas. Cation-selective membranes result in predominantly water and sodium ions migrating to the cathode, where water is reduced to produce hydrogen gas and hydroxide ions and the hydroxide and sodium ions combine to form sodium hydroxide. This process results in the production of 30-35% sodium hydroxide that can be concentrated further using evaporators.
Mercury cell	Elemental mercury flowing along the bottom of the electrolyzer acts as the cathode, anodes are suspended parallel to the base of the cell, a few millimeters above the mercury. Brine fed into one end of the cell flows by gravity between the anodes and the cathode; chlorine gas is evolved and released at the anodes while sodium ions are deposited along the surface of the mercury cathode. The alkali metal dissolves to form a liquid amalgam with the mercury cathode, which then flows by gravity to a carbon-filled decomposer where deionized water is added to strip the alkali metal from the mercury, producing hydrogen and sodium hydroxide. Mercury is then pumped back to the cell inlet and reused.

Modified from The Chlorine Institute (2008)

NB: Chlorine can also be produced through the electrolysis of molten sodium or magnesium chloride to produce elemental sodium or metallic magnesium, through the electrolysis of hydrochloric acid, and through non-electrolytic processes.

APPENDIX B

TABLE B.1: Semi-structured interview questions for Kazakhstani research scientists

Have you spent any time in Pavlodarskye?
 Yes: Would you consider it safe to live there? No: Why not?
What are your thoughts on mercury? What can you tell me about it?
As you know, there was a mercury spill at the Khimprom Plant. When did you hear about this spill?
What did you first hear about it?
Do you feel affected by this spill?
 Yes: Why? How do you feel that the spill affects you? No: Why not?
Why did you get involved in the clean-up of the mercury spill at the Khimprom Plant?
What do you think would be the best solution to the mercury spill?
Do you plan to remain involved with this site in the future? If yes, how?
Who do you think is most at risk from the mercury spill? Why?

TABLE B.2: Semi-structured interview questions for Khimprom Plant workers

For Site Workers and Plant Management

How long have you worked at the Khimprom Plant?
Do you live near the Khimprom Plant?
 No: Where do you live? Have you ever lived near the plant?
What can you tell me about mercury?
Did you know that there was a mercury spill at the Khimprom Plant?
 Yes: When did you hear about this spill? What did you hear about it?
 Do you feel affected by this spill?
  Yes: Why? How do you feel that the spill affects you? No: Why not?
What is your job at the Khimprom Plant? Where do you spend your time?
How many hours per day do you work?
Do you wear any protective equipment when doing your work?
Do you think there is a problem with mercury at the Khimprom Plant?
 Yes: What do you think would be the best solution to the problem? No: Why not?
Who do you think is most at risk from the mercury spill? Why?
What has been done so far?

For Plant Management Only

How long do you think it will take to achieve a reasonable solution to the mercury spill? Or do you feel that it has been reached already and must be monitored?
What do you think would be the best solution to the mercury spill? Who should be involved?

TABLE B.3: Semi-structured interview questions for Pavlodarskye villagers

Have you lived in Pavlodarskye all your life?
 No: How many years have you lived in Pavlodarskye?
Have you ever heard of mercury?
 Yes: When did you hear about this spill? What have you heard about it?
Do you feel affected by this spill?
 Yes: Why? How do you feel that the spill affects you? No: Why not?
Do you fish in Lake Balkyldak?
 Yes: Have you not heard that it is against the law to fish in this lake? Do you know this lake is affected by the mercury? Why do you still fish in this lake?
 No: Have you heard that it is against the law to fish in this lake? Is that why you do not fish in the lake? Otherwise, what is the reason?
Do you fish in the River Irtysh? Why/why not?
Where do you get your water from?
Do you grow vegetables on your land? Raise meat?
 Yes: Where do you get water for your garden? No: Where do you buy your food?
Do you think there is a problem with the mercury spill at the Khimprom Plant?
 Yes: What do you think would be the best solution to the mercury spill? No: Why not?
Who do you think is most at risk from the mercury spill? Why?