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Local impacts of coal mines and power plants across Canada

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Local Impacts of Coal Mines and Power Plants across Canada

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MANAGEMENT PERSPECTIVE

This is part of Environment Canada's Action Plan (Conserving Canada's Ecosystems) addressing local impacts of coal mining and coal-fired power plants. Are the surrounding waters and sediments elevated by these operations in term of trace metals (such as Tl, Hg, Cd), organics such as PAHs, and toxicity to four invertebrate species ?

Eastern Canada has higher thallium concentrations in its waters than the western and central regions in spite of its lower production and consumption of coal. Data seem to indicate that it is not the amount but the type of coal used and/or the local geochemical contributions that are responsible for some of the very high Tl concentrations observed. In sediments, several concentrations of pollutants were elevated and very high toxicities were observed at both the mine and power plant sites. Thallium enrichment, as well as non-biological origins of sediments, were found.

Detailed toxicity tests along with chemical analyses be followed-up at least for the sediments from the Prince colliery, Battle River, Phalen colliery, Trenton and Belledune power plants, as well as Salmon Harbor mine.

SOMMAIRE À L'INTENTION DE LA DIRECTION

La présente étude fait partie du plan d'action d'Environnement Canada (Conservation des écosystèmes du Canada) et examine les impacts des mines de charbon et des centrales thermiques alimentées au charbon dans les régions. L'exploitation de ces mines et centrales augmente-t-elle dans les eaux et sédiments des alentours les concentrations de métaux traces (tels que le Tl, le Hg, le Cd) et de substances organiques (telles que les HAP) et la toxicité du milieu pour quatre espèces d'invertébrés étudiées?

Même si l'Est du Canada produit et consomme moins de charbon que les régions de l'Ouest et du Centre du pays, ses eaux présentent des concentrations de thallium (Tl) plus élevées. Les données semblent indiquer que ce n'est pas la quantité, mais bien le type de charbon utilisé et les propriétés géochimiques locales qui sont responsables des très fortes concentrations de Tl. On a observé plusieurs concentrations élevées de polluants ainsi qu'une très forte toxicité dans les sédiments prélevés aux sites des mines de charbon et des centrales thermiques au charbon. Un enrichissement en Tl et des sédiments d'origine non biologique ont également été trouvés.

On devrait poursuivre des essais de toxicité détaillés et des analyses chimiques des sédiments au moins pour les charbonnages de Prince, de Battle River et de Phalen; les centrales thermiques de Trenton et de Belledune; et la mine de Salmon Harbor.

Abstract

A Canada wide survey was undertaken of sites associated with coal mines and coal-fired electrical generating stations. Some sites were severely impacted by high concentrations of metals, organics and high toxicity to invertebrates. Several sites in eastern Canada were found to contain high thallium concentrations, in spite of the greater coal consumption and production in the western and central regions. The data suggest that coal type (rather than quantity) and/or regional geological contributions are responsible for the high Tl concentrations observed. Our findings coupled with others around the world strongly indicate that Tl is an environmental pollutant. In sediments, several elevated metal and PAH concentrations, as well as high toxicity (based on biological sediment guidelines) were observed compared to uncontaminated sites. Compared to crustal concentrations, the observed Tl/Hg ratios suggest there is an enrichment of Tl by at least 25%. The observed diversity of PAHs and near-unity carbon preference indices indicate non-biological origins of the studied sediments. In this initial study, four different organisms, *Chironomus riparius, Hyalella azteca, Hexagenia spp. (Hexagenia limbata)* and *Tubifex tubifex* were used to determine sediment toxicity, which showed fifty percent of the tested sites were highly stressed.

Key words: coal mine, power plant, sediment quality guidelines, metal pollution, thallium pollution, organics, carbon preference index, toxicity, biological sediment guidelines, bioassay endpoint, ordination space.

Résumé

On a effectué un relevé pancanadien des sites associés aux mines de charbon et aux centrales électriques alimentées au charbon. Certains sites examinés contiennent de très fortes concentrations de métaux et de substances organiques, et présentent une toxicité élevée qui peut nuire aux invertébrés. Dans l'Est du Canada, plusieurs sites ont des concentrations plus élevées de thallium (Tl) que les régions de l'Ouest ou du Centre et ce, bien que la consommation et la production de charbon soient moindres dans l'Est. Les données recueillies indiquent que c'est le type de charbon (plutôt que la quantité) et les propriétés géologiques régionales qui sont responsables des concentrations élevées de Tl. Ces constats ainsi que d'autres études réalisées ailleurs dans le monde laissent fortement croire que le Tl est un polluant de l'environnement. On a observé des concentrations de métaux et d'HAP et une toxicité plus élevées (selon les lignes directrices sur la qualité des sédiments) dans les sédiments prélevés sur les sites étudiés que dans ceux des sites non contaminés. Comparativement aux concentrations crustales, les rapports Tl/Hg observés montrent qu'il y a un enrichissement en Tl d'au moins 25 % dans les sédiments contaminés. La diversité des HAP et les indices de préférence du carbone proches de l'unité révèlent les origines non biologiques des sédiments étudiés. Dans l'étude initiale, quatre organismes différents, *Chironomus riparius, Hyalella azteca, Hexagenia* spp. *(Hexagenia limbata)* et *Tubifex tubifex*, ont été utilisés pour déterminer la toxicité des sédiments. Les résultats montrent que 50 % des sites examinés subissent d'importants facteurs d'agression.

Mots-clés : mine de charbon, centrale électrique, lignes directrices sur la qualité des sédiments, pollution par les métaux, pollution par le thallium, substances organiques, indice de préférence du carbone, toxicité, lignes directrices sur la qualité des sédiments biologiques, résultats des bioessais, espace de l'ordination.

Introduction

Coal is Canada's most abundant fossil fuel. Its production and consumption exceed 78 and 55 million tonnes, respectively (Table 1, Canadian Coal Statistics 1997). Across Canada there are thirty- five active coal mines and twenty five coal-fired generating stations (Tables 2 - 3). Coal is also important to the Canadian economy, and its exports are worth $2 billion (Natural Resources Canada 1994).

However, the effects of coal production and consumption may be detrimental to the environment. For example, Smith and Carson (1977) reported that the air emissions from the 415 American coal-burning power plants in highly populated regions form the largest collective source of thallium (Tl) discharged atmospherically. Four States around the Great Lakes (including Ohio), along with Texas, have the highest coal-fired generating capacity in excess of 15,000 Megawatts of electrical power. Indeed we recently found that the concentration of dissolved Tl in the Great Lakes waters particularly Lake Erie is higher than that of Cd. These two facts led us to suspect that high concentrations of Tl and other metals as well as organics may be found surrounding coal mines and coal-based power plants, with consequent environmental effects. This initial study describes a Canada wide survey of local impacts of coal mines and power plants in terms of chemical pollutants and toxicity to aquatic invertebrates.

Experimental

Mines and power plants in Canada

The study was designed to include all Canadian active coal mines and coal-burning electrical power plants (generating stations), the locations of the principal ones being shown in Figures 1 and 2. These mines have a saleable production of coal ranging from 0.27 million tonnes by NB Coal to 12.7 million tonnes by Highvale (Canadian Coal Statistics 1998). Alberta and other western provinces have more plants and mines than the eastern and central provinces combined. Most of the sites were accessible and therefore sampled, and the remaining sites were either closed or inaccessible as access permission was not provided.

The following companies provided permission to collect water and sediment samples from their sites -- Alberta Power Limited; Cape Breton Development Corporation; Edmonton Power; Luscar Ltd.; Manalta Coal Ltd. / Prairie Coal Ltd. Mines; Manitoba Hydro; NB Coal Limited; New Brunswick Power Corporation; Nova Scotia Power; Ontario Hydro; Quinsam Coal Corporation; SaskPower; Smoky River Coal Limited; and TransAlta.

Sampling protocols

At each sampling location (a mine or a generating station), there are at least three sampling sites: water intake such as upstream of a river, water discharge after the intake has gone through all necessary processes, and water at the tailing/disposal site such as downstream or pond. Additional samples such as those from settling lagoons, nearby lakes and rivers are also included if available.

Bottle washing

All containers were washed as follows: rinse with hot tap water and empty well; soak with 30% nitric acid for at least one week; rinse with MQW six times; soak with 0.2% nitric acid (high purity) for a minimum of one week before use. Sub-boiled Seastar acid was used to preserve samples.

Water sampling

Van Dorn bottles were used whenever possible; if the Van Dorn bottle was inappropriate, a “scoop” technique was used, where a "sampling bottle" (250 ml bottle) was scooped to an arm-length depth under water surface. A sample bottle was rinsed three times with actual sample first before it was filled up to top. Standard precautions were followed such as; avoid touching the bottle rim throughout sample collection and handling; tighten bottle caps tightly to avoid cross contamination due to possible leakage during transportation; bag blanks separately from samples; store samples in ice chest immediately; collect sediments last and bag them completely separated from water samples. A total of two hundred seventy nine different samples were collected.

Sediment sampling

This study selected several sites for initial examination. Thirty- two sediment samples were collected, seventeen from power plant sites and fifteen from mine sites. A mini ponar sampler (1-2L) or an Eckman sampler was used to collect sediment samples. For trace metals and bioassay tests, all containers, bags, spoons, and other utensils used were in plastic; glass bottles were used to collect sediment samples for organic parameters. Sediment samples were collected after water collection.

Collection of blanks and duplicate samples

The collection of blanks using Van Dorn bottle was done as follows. Onsite and just before collecting the first upstream water sample, a Van Dorn bottle was rinsed very well with 1 litre of ultrapure water. The last part of the rinsing water was collected into a small bottle marked "Blank Before". Then the upstream water sample was collected in duplicate, by rinsing then filling two separate small bottles to the rim. The "Blank After" was then collected by rinsing the Van Dorn bottle with one litre of ultrapure water, the last part of which was saved as blank.

The collection of blanks using "scooping" technique was similarly processed as above. Onsite and just before collecting the first upstream water sample, a 250 ml "sampling bottle" was rinsed 3 times with 20-30 ml of ultrapure water and the 4th rinse was saved as "blank before". The upstream water sample was then collected in duplicate, by scooping the 250 ml bottle into an arm-length depth and by rinsing then filling two separate small bottles to the rim. The "blank after" was obtained as above by collecting the 4th rinse. In total, about 7% of samples were blank samples. More than 40% of samples were measured for pH before acidification to give an idea of the sample acidity. Most samples had pH between 7 and 8. Duplicate samples for discharge and downstream sites were collected as above.

Separate bagging

Samples for blanks, upstream, discharge, downstream, and sediment were bagged separately to avoid cross-contamination.

Sample collection, handling, and preservation

Water samples were refrigerated immediately after collection and maintained at 4°C. When in our laboratory, the samples were allowed to settle in a 4°C room overnight or over the weekend. The clear samples i.e. those without visible particulates were preserved by acidifying the whole bottle content to 0.2 % HNO_3. From the samples with visible particulates settled at the bottom of the bottle, twenty milliliters of the clear upper layer was pipetted (called decantate) into a clean container and preserved at 0.2 % HNO_3. The samples with suspended materials were centrifuged and the decantate acidified. Those samples, which were cloudy due to suspension or naturally colored due to humic substances, were centrifuged and acidified as above. Samples with high salt content as evidenced by severe peak height suppression during analysis were diluted 10 times or more until the suppressive effect was manageable.

Sediment samples were refrigerated at 4°C until use. For inorganic and organic parameters, 250 ml bottles were used to contain wet sediments which were freeze-dried, crushed, sieved, and sub-sampled for the analysis of heavy metals, Hg, Tl, and organics (15-60 g). For toxicity tests and for each site, five one-liter replicate samples (for five replicate tests) were collected and placed into plastic bags, and refrigerated.

Analytical methods and analytes

Trace metals in waters and sediments were determined using ICP-AES. Thallium, undetected in both substrates by this technique, was determined by the LEAFS (Laser-Excited Atomic Fluorescence Spectrometric) methods recently developed by Cheam et al. (1996; 1998). The method for water analysis has a detection limit of 0.03 ng/L of thallium. Mercury in sediments was determined by the cold vapor atomic absorption spectrometry. Sediments were analyzed by GC-MSD for PAHs, PCBs, and n-Alkanes. Naphthalene results, due to the possible loss during the freeze-drying process (Fox et al. 1991), may be low by 20-50%.

Toxicity tests

Detailed procedures have been described previously (Reynoldson et al. 1991; 1994). For removal of large debris and endemic species, culture water was added to the sediment producing a slurry, which was then poured through a 250μm mesh screen (Reynoldson et al. 1991),. Sediment was then allowed to settle for 24 hours. The water was decanted and used as the overlying water in the tests. However, most sediments did not pass through the sieve. As a result, the *Tubifex tubifex* test could not be performed on the Salmon Harbour sample. There were a large number of endemic worms present in this sample that made it difficult to identify *T. tubifex*. Total ammonia readings were taken at the completion of the tests. The bioassay tests were performed as follows.

Chironomus riparius : The 10-day survival and growth test was performed. The endpoints were expressed as percent survival and average growth given in mg dry weight per individual organism per replicate.

Hexagenia spp. : The 21-day survival and growth test was done, and the endpoints were expressed as above.

Hyalella azteca : The 28-day survival and growth test was done, and the endpoints were expressed as above.

Tubifex tubifex : The 28-day adult survival and reproduction test was carried out. The endpoints were expressed as a) the number of adults surviving out of 4; b) the number of cocoons produced per individual adult worm and the percentage of those cocoons that hatched; and c) the number of youngs produced per individual adult worm.

Sediment toxicity was determined by ordination of the 10- endpoints from the study sites with data from 116 reference sites. Probability ellipses were constructed around reference sites only (90, 99, and 99.9 %). Study sites inside the 90% probability ellipse were considered non-toxic. Those outside the 90% ellipse were considered toxic to various degrees.

Results and Discussion

Heavy metals in waters

Metals determined by ICP included Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Tl, and Zn. Seventy nine percent of the total data showed “less than” values, and of the 21% reportable positive results more than half were Fe and Mn results. For the Highvale Mine, the "pit 2 drain" site contained up to 70 mg/L of Fe and positive results for other metals except Pb and Tl. The "pit 3 settling pond" inflow had 40 mg/L of Fe compared to only 0.01 mg/L for the outflow; for other metals also, the inflow concentration was greater than the outflow, indicating an effective removal mechanism of metals in the settling pond. It was interesting also to note that the Fe concentration of the local groundwater (well water) contained a high Fe concentration of 20 mg/L. The three sites also had positive but relatively low results, < less than 1 mg/L, for Mn and most other metals.

The impoundment #5 discharge of the Paintearth Mine contained a very high Fe concentration of 122 mg/L. This mine is located by the Paintearth Creek whose upstream Fe concentration was fairly high at 1.5 mg/L and downstream concentration at 7 mg/L. Also the mine's runoff discharge contained 10 mg/L of Fe. The coal pile runoff of the Lingan Generating Station had a high Fe content of 72 mg/L and 4 mg/L of Mn, but the waste water discharge to lagoon and ash lagoon return contained less than 1 mg/L of Fe and 2 mg/L of Mn, respectively. Other sites containing more than 1 mg/L of Fe included the spoil pond 5-5 of the Boundary Dam Generating Station; the ash lagoon slurry of the Keephills Generating Station; and the settling pond discharge MSA of the Line Creek Mine. The sites at the Belldune Generating Station had high Mn concentrations, the treated discharge containing 73 mg/L, the equalization pit 55 mg/L and the coal pile runoff 14 mg/L of Mn. On the other hand, Fe concentrations in these sites were less than 1 mg/L. These sites also contained positive results of Ni and Co.

Besides Fe and Mn, Nickel had only 24% of its data as reportable positive results and Cobalt had 22%. Other metals had lower percentages; Cr 18%; Zn 16%; Cu 11%; Pb 6%; Cd 1%; and Tl 0%. Since Tl is a very toxic element and of particular importance due to the statement by Smith and Carson (1977), that the air emissions from coal power plants form the largest collective source of Tl discharge into the environment, Tl was also analyzed by the LEAFS method and is discussed below. For all the metals analyzed, the upstream metal concentrations were found to be smaller than the downstream, discharge or pond concentrations ninety five percent of the time.

Table 4 shows Tl results in western coal mine waters. Samples with brown - black deposit and brown decantate such as those from Highvale and Paintearth mines tend to have higher Tl concentrations than other samples. For three such samples from the Highvale mine, centrifugation did not help bring down Tl concentration of the decantates. It appears that decantation (careful pipetting of 20 ml of the solution above the deposit) was representative of the water samples. Also samples from settling pond, pit water, downstream and discharge usually had concentrations (1100 - 1300 ng/L) higher than those from upstream or water intakes (low ng/L). The eastern mines, including the abandoned ones, showed some high concentrations of about 700 ng/L (Table 5). Although these concentrations were not as high as those observed in the eastern power plant sites (discussed below), they may have come from the same Tl sources.

The majority of results for the generating stations in western provinces were low (Table 6). The blank values ranging from 0 to 6 ng/L were considered acceptable as the clean room practices (clean hood, special clean clothes or gloves) were not followed since it was deemed unnecessary to use them in this study. The results for discharge water, ash lagoon, ash slurry or downstream were higher than other locations but even the highest results – 97 ng/L for Long Creek below Boundary Dam Reservoir, or 140-150 ng/L for

Keephills ash lagoon slurry – were low when compared to the high results of some sites to be discussed below.

Samples collected from the eastern power plants sites in New Brunswick and Nova Scotia generally contained higher Tl content than the western or central counterparts (Table 7). For example the ash lagoon discharges of Grand Lake power plant and Trenton power plant contained some 12000 ng/L and 24000 ng/L of Tl, respectively. The other generating stations such as Belledune, Lingan, Point Aconi and Point Tupper also had elevated concentrations of Tl up to 5000 ng/L. These levels could be the result of the local geological contribution in the eastern provinces, or the type of coal used. Belledune Generating Station for example reportedly had been using 75% Columbian coal and 25% Salmon Harbor coal. The Tl concentrations in the central (Ontario) sites were relatively low, the highest being only 175 ng/L (Table 7) and the mean value 38 ng/L. The western sites had a mean value of 47 ng/L (range 0 – 1326 ng/L), whereas the eastern sites' mean value was 1376 ng/L (range 0-23,605 ng/L). Even if we include the Tl concentrations in lakes around the Inco smelters in Sudbury (Ontario), which we recently measured, the mean value for central region would still be small. Also several water samples collected from Quebec Province were found to contain small Tl concentrations.

Even though the Great Lakes are surrounded by the biggest consumers of coal used in coal - fired generating stations in both USA (Figure 3) and Canada (Table 8), the concentration of Tl in Great Lakes waters (Cheam et al. 1995) were much lower than those found in waters from the eastern generating stations (Table 7). Also the numerous power plant and mine sites in western and central Canada contained smaller amount of Tl than the eastern counterparts. These two facts tend to indicate that it is not the amount but the type of coal used and/or the local geochemical contributions that caused some of the higher Tl concentrations observed in the eastern provinces. Chou and Uthe in 1995 had observed high Tl content in the Belledune Harbor although the source of Tl was obscure, though they suspected the nearby fertilizer plant and the lead smelter as well as the power plant were the sources of thallium. Also Zitko et al. (1975) reported very high Tl concentrations (up to 88,300 ng/L) in South Tomogonops River, Little River and South Little River within North Eastern New Brunswick. South Tomogonops and South Little River received discharges from base-metal mining operations. Wong (personal communication) had found very high Tl content in some local sediment samples, such as those from Upsalquitch Lake. These high Tl concentrations found in Canada (24,000 ng/L near a power plant and 88,300 ng/L in a mine waste) are by no means alone as there are numerous other high concentrations found around the world, some of which are; the hot springs in New Zealand contain 7,000 ng/L of Tl; a table mineral water in Germany- 3,500 ng/L; a cement plant waste water in Germany- 20, 000 ng/L; an oil drill waste water in USA- 672,000 ng/L; a smelter waste in Germany- 800,000 ng/L; and a mining waste in Germany- 23,000 ng/L (Schoer 1984). It is obvious that Tl, being a highly toxic element, is a global environmental concern.

Heavy metals in sediments

Table 9 gives the concentrations of heavy metals as determined by ICP, as well as those of Tl and Hg as determined respectively by LEAFS and CVAAS. (ICP results for Tl were all less than values). The concentrations of thallium were in general similar to other Tl concentrations reported around the globe for sediments (Cheam 1999; Cheam et al. 1998), except one very high concentration found in the Obed Mountain Coal main tailings pond sample, which had a concentration of 3.39 μg/g. As a comparison, the highest concentration of Tl reported in the world's sediment reference materials was 2.9 μg/g, which was certified for a Chinese stream sediment (Govindaraju 1994). Of interest also, the highest concentration found in the Great Lakes reference materials was 2.6 μg/g; this sediment was from Hamilton Harbor (Cheam et al. 1998). Other fairly high concentrations, ~ 1 μg/g of Tl, were found in the Sundance Generating Station ash slurry sample; in the Keephills Generating Station ash lagoon cenospheres sample; in the Genesee Mine drainage sample, the Line Creek Mine settling pond, and Phalen Colliery surface runoff brook. Most of the Tl concentrations were, however, below 1 μg/g.

Mercury is likely the most studied element among the toxic metals because of the well - known bioaccumulation of the highly toxic compound methyl mercury, not because of its high concentration. In fact, its concentration in the environment is usually quite low compared to other toxic metals, and this study confirms it. Table 9 shows the concentrations of Hg were much lower than other meals including Tl. The concentration differential between Tl and Hg is similar to the one found by Lentz in 1993 for the concentrations found in a massive sulfide deposit at Bathurst, New Brunswick. Also this difference occurs in most of the world's sediment reference materials (Cheam 1999). Similarly, the earth's crust content is 450-600 ppb of Tl, compared to only 200 ppb for Cd and 80 ppb of Hg (CRC Handbook 1992-93; Korenman 1963). The crustal rocks concentrations of Tl is also higher than that of Hg and Cd -- 530 ppb of Tl vs. 150 ppb of Cd, and 67 ppb of Hg (Winter 1998). These crustal concentrations give the Tl/Hg ratios of 5.6 to 7.9, whereas the ratios for the 10 samples investigated range from 6 to 39, with a mean value of 13 and a median value of 10. The ratio values suggest there is an enrichment of Tl by at least 25%, or even as high as 117%, which indicates Tl input from other sources.

For the Souris River sediment, the concentrations of Tl and Hg were higher in the upstream samples than the downstream samples (Table 9). The same was true for other heavy metals. To verify the findings, new fresh and duplicate samples from the same locations were recently collected and analyzed for heavy metals. The new results confirmed the higher concentrations in the upstream sediment compared to downstream. This was in fact true for organic compounds as well as toxicity to various organisms to be discussed below. Also, for water samples, the upstream samples likewise contained higher Tl content than downstream. It seems therefore that the so-called "upstream" sediment sample (49° 07.337' latitude N., 103° 01.397' longitude W.) may in fact represent the outflow of the cooling water from the Boundary Dam Generating Station (Smith 1999).

It is also interesting to note that the Battle River upstream sediments also contained higher concentrations than the downstream sediments for all groups of chemicals, except perhaps Tl and Hg; we have no explanation for this. The Phalen Colliery sediment contained, by far, the highest Cd content (16.2 μg/g, all other sediments were <3.4 μg/g) and the highest Fe content (17%, the closest being 5.8%). These two concentrations were even higher than those found in five different sediment cores from Hamilton Harbor (Zeman et al. 1995) and would put the sediment in the class of "grossly polluted" according to the Ontario's sediment quality guidelines (Table 10; Jaagumagi and Persaud 1995). However, the Cr, Pb, Mn, Ni and Zn data would place the sediment in the "marginally- significantly polluted" category only. In addition to these metals, the sediment also had high concentration of Tl and Co (Table 9).

The 8200 Salmon Harbor Mine also had two very high levels in Fe and Mn, which would qualify the sediment as grossly polluted (Table 10). But the Cr, Ni and Zn data would classify the sediment quality as "marginally- significantly polluted". This sediment also had the highest Co concentration compared to the other sediments studied (Table 9). The Trenton Generating Station, on the other hand had the highest concentrations of Cu and Pb, and would be classified as "marginally- significantly polluted" based on the Cr, Fe, Pb, Ni and Zn data (Table 10). The Prince Colliery sediment had a high Fe concentration of 3.7 % (close to the "severe effect level" of 4 %) and high enough concentrations of Cr, Mn and Ni to put it in the "marginally- significantly polluted" category. All other sediments also belonged to this category by virtue of at least one high concentration of an element.

All Ni data indicated that 81% of the sediments would fit in the sediment quality "marginally- significantly polluted" class. The percentages of sediments falling in this class were; 77% based on Cr data; 61% on Fe data; 26% on Mn data; 16% on Pb data; and 3% on Zn data (Tables 9 and 10).

Organics in sediments

Polycyclic aromatic hydrocarbons (PAHs)

The sixteen PAHs that are priority pollutants were measured. In addition, two 252 PAH isomers, benzo[e]pyrene and perylene, were also quantified using the benzo[a]pyrene response (Table 11). Most samples were found to contain small amount of these compounds. However, the concentration of total PAHs in the Prince Colliery downstream discharge sample (sample 141S) is high as it is in the same order of magnitude as that of the polluted Hamilton Harbor suspended sediments (RAP 1988; Mayer and Nagy 1992). The diversity and high levels of the PAHs in samples 209S, 128S and 141S in particular (Table 11) compared to the other sites seemed to suggest that these sites were affected by industrial inputs associated with coke production (Mayer and Nagy 1992). For sample 141S, the concentration of several PAHs including naphthalene and phenanthrene exceeded the "lowest effect level" of the Ontario's guidelines for sediment quality. The same is true for total PAHs, whose concentration of 11.2 μg/g exceeded the lowest effect level of 4 μg/g, thus putting this sediment well into the "marginally-significantly polluted" class (Jaagumagi and Persaud 1995).

n-Alkanes

The determination of n-alkanes helped determine the types of sediments, whether they were of biological or petroleum origins. According to Bray and coworkers (Bray and Evans 1961; Cooper and Bray 1963), the types can be inferred by determining the carbon preference index (CPI) from the odd-carbon and even- carbon data in the sediments of interest. The CPI is defined for the number of carbon up to 26 as

$CPI = \frac{1}{2} [A/B + A/C]$, where

$$A = \sum_{13}^{n-1} \text{odd-carbon alkanes,}$$

$$B = \sum_{14}^{n} \text{even-carbon alkanes, and}$$

$$C = \sum_{12}^{n-2} \text{even-carbon alkanes}$$

The CPI's for biological systems range about 2.5 - 5.5, whereas the CPI's of about 1 indicate crude oil or petroleum systems. In our case, the CPI's range from 0.8 to 1.7 (Table 12) with an average of 1.3 ± 0.3, which clearly indicates non-biological origins.

The Prince Colliery downstream discharge sample contained the highest total n-alkanes of 32 μg/g, but the smallest CPI of 0.8, which signifies an industrial system, thus corroborating with its PAHs data as discussed above. Likewise, the Souris River upstream sample containing a fairly high n-alkane concentration of 7 μg/g and a low CPI of 1.5 would be of industrial sources.

Polychlorinated Biphenyls

The analysis of PCBs showed that the concentrations were very low, and only very few congeners were detected. In fact, of the 360 congeners analyzed (40 congeners per sample times 9 samples), only 36 congeners were detected sparingly as above or close to the detection limit of 20 pg/g.

Sediment toxicity

Toxicity endpoints

Reynoldson et al. (1997) reported on sediment toxicity targets in the recently published biological sediment guidelines for the Laurentian Great Lakes. In that report, they established toxicity limits for determining toxicity of ten test endpoints. Using the sediments from the Great Lakes reference sites, they classified sediments as non-toxic, potentially toxic, and toxic, based on the percentage of survival and growth of three different organisms, namely, *Chironomus riparius, Hyalella azteca,* and *Hexagenia spp. (Hexagenia limbata).* As well, the survival and reproduction targets were established for the oligochaete worm *Tubifex tubifex*, based on % survival, % hatch, # cocoons/adult, and # youngs/adult. These guidelines are used in determing the toxicity of the sediment samples.

Table 13 shows the % survival and the growth of the test species *Chironomus riparius* in five sediments from the various regions. It indicates that the sediments from the Battle River Power Plant (16%) and the Prince Colliery (40%) would be classified as toxic, based on the % survival "toxic" limit of <60% (Reynoldson et al. 1997). However, on the growth basis, all five sediment types would be classified as non-toxic since all the five growth results fell within the non-toxic range of 0.21-0.49 mg dry weight.

The sediments used would be indexed as non-toxic to *Hexagenia spp.* organisms as all the growth values fell within the non-toxic confine of 1.0-5.0 mg (Table 13). Furthermore, all the % survival values were greater than the non-toxic limit of >85.

Hyalella azteca were much affected by the Prince Mine sediment as both the % survival and the growth were below the "toxic" limits -- 36.7% << 58% and 0.1 < 0.11 mg, respectively (Table 13). The high amount of ammonia of 9 ppm produced from this sediment, the highest ammonia content observed in the study, may have contributed to the observed high sediment toxicity. Of all sediments, the Prince Mine sediment also produced the highest ammonia content for every organism studied. Additionally, an examination of the chemical data revealed that the very high content of the PAHs in the sediment (Table 11), as discussed above, may have contributed to the observed high toxicity. The sediment also contained the highest content of n-alkanes (Table 12). *Hyalella azteca*, on the other hand, were not as affected by the other sediments, except the Battle River sediment, which may be potentially toxic to *Hyalella* based on the % survival of 68, which is right at the edge of the "potentially toxic" range of 58-67.9.

Table 13 also shows the toxicity results for *Tubifex tubifex*. The sediment from the Battle River Generating Station would be classified as toxic since the #cocoons/adult, 5.2, was below the toxic limit, <5.9; furthermore, the % survival as well as the #young/adult were within the "potentially toxic" limits of 84-87.9 and 3.6-11.9, respectively. However, the chemical data (Tables 4-7 and 9-12) did not seem to corroborate with the toxicity results since the Battle River sediment contained no real high concentrations of any metals, PAHs, n-alkanes, or PCBs relative to other sediments. So it is interesting that the Battle River sediments were toxic to three out of four test species in spite of its relatively low chemical concentrations. It could be that the Battle River sediment contained more toxic organic matter than the other sediments, or they could contain other highly toxic contaminants not measured in this study.

Integration of toxicity endpoints

To integrate all the results from the toxicity endpoints we have used an ordination method. Ordination reduces the variables required to identify the structure of the data. A non-metric hybrid multi-dimensional scaling (MDS) method of ordination was used (Belbin 1991). Hybrid multi-dimensional scaling methods use metric and non-metric rank order rather than metric information and thus provides a robust relationship with biological distance. It does not assume a linear relationship, an inherent assumption in some dissimilarity measures used by other ordination techniques (Faith et al. 1987). This method also down-weights those end points which are highly correlated, thus avoiding problems of "double counting" associated with single endpoint comparisons.

To assess the significance of the responses at the exposed sites we have ordinated the results from reference sites, with the coal mine/power plant sites and plotted these data in the same ordination space. If an exposed mine/power plant site is within the range of variation observed at reference sites we would assess it as equivalent to reference, if it is outside the range observed at reference sites we would assess it as toxic. A large river quality survey conducted in the UK in 1990 provided the impetus for the development of methods to circumscribe the continuum of biological response into a series of bands that represented grades of biological quality from good to poor (Wright 1995; Wright et al. 1991). Despite the simplification, it was seen as an appropriate mechanism for obtaining a simple statement of biological quality, allowing broad comparisons in either space or time that would be useful for management purposes.

We have adopted a similar approach for defining degrees of difference from the reference condition using a multivariate approach, and based upon three probability ellipses (Fig. 4) constructed around reference sites. Sites inside the smallest ellipse (90% probability) would be considered *equivalent to reference, or non-toxic*; sites between the smallest and next ellipse (99% probability) would be considered *possibly different, or possibly toxic*; sites between the 99% probability and the largest ellipse (99.9% probability) would be considered *different, or toxic*; and sites located outside the 99.9% ellipse would be designated as *very different, or very toxic.*

Figure 4 shows the results from reference sites (open circles) and 5 mine/plant sites where only six end points were measured (no data for *T. tubifex*). The five sites are described earlier. The results from the six end points could be explained by two ordination axes. Two sites from SR (Souris River) showed no evidence of toxicity; one site (SHM, Salmon Harbor Mine) would be considered toxic; and two sites were very toxic (PM = Prince mine, and BRGS = Battle River Generating Station). The four sites for which all ten test endpoints were available required three ordination axes to explain the variability in test response (Figures 5-7). Again the two sites (PM and BRGS) were identified as very toxic, and the two SR samples were non- toxic. The results from the ordination method agree well with those from the toxicity end points method. It seems therefore that the ordination technique is a powerful, effective graphical presentation to determine the toxicity of sediment.

Conclusions

1. This initial study surveyed the local impacts of coal- mines and coal- based power plants across Canada. Some sites were severely impacted by high concentrations of metals, organics and high toxicity to invertebrates.
2. For the metals in water samples, the upstream concentrations were found to be smaller than the downstream, discharge or pond concentrations ninety five percent of the time.
3. Some very high thallium concentrations were found in the eastern region near power plants. Since the western and central regions produced and consumed more coal than the eastern region, it was concluded that the coal type, not its amount, and/or the regional geological contributions were responsible for the observed high levels.
4. In addition to Canada, other countries also saw some very high thallium levels reported, which implies that thallium is a global environmental pollutant.
5. Most of the studied sediments fell in the "marginally-significantly polluted" category of sediment quality, although two belonged to the "grossly polluted"

class, based on Ontario's sediment guidelines. This was due to the extremely high concentrations of some metals.

6. Fifty percent of the sediments tested, using bioassay end points and ordination techniques, were found to be highly toxic.

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Table 1. The production, consumption, import, and export of coal, tonnes, in Canada

	Production	Consumption	Import	Export
British Columbia	27,892,747	200,817	---	27,278,581
Alberta	36,343,416	26,264,343	---	9,181,069
Saskatchewan	11,652,553	10,018,189	---	---
Manitoba	---	263,829	185,572	---
Ontario	---	13,877,042	11,393,496	---
Quebec	---	732,265	750,265	---
New Brunswick	170,958	1,326,676	1,150,622	---
Nova Scotia	2,632,994	3,051,199	--	49,924
Total	78,692,668	55,734,360	13,479,955	36,509,574

Table 2. List of all active coal mines in Canada (by province)

Principal mines (1997 data/ The coal Association of Canada)

British Columbia	Owner
Quinsam	Quinsam Coal Corp.
Bullmoose	Teck Corporation
Quintette	Teck Corporation
Fording River	Fording Coal Ltd.
Greenhills	Fording Coal Ltd.
Line Creek	Line Creek Resources Ltd.
Elkview	Teck Corporation
Coal Mountain	Fording Coal Ltd.

Saskatchewan	Owner
Poplar River	Manalta Coal Ltd.
Utility	SaskPower
Boundary Dam	Luscar Ltd.
Costello	Manalta Coal Ltd.
Shand	Luscar Ltd.
Bienfait	Luscar Ltd.

Alberta	Owner
Smokey River	Smokey River Coal Ltd.
Obed	Luscar Ltd.
Highvale	TransAlta Utilities Corporation
Whitewood	TransAlta Utilities Corporation
Luscar	Luscar Ltd.
Gregg River	Manalta Coal Ltd.
Coal Valley	Luscar Ltd.
Genesee	Edmonton Power & Fording Coal Ltd
Vesta	Alberta Power Ltd.
Paintearth	Luscar Ltd.
Montgomery	Manalta Coal Ltd.
Sheerness	Luscar Ltd.

New Brunswick	Owner
N. B. Coal (Minto)	N. B. Coal Ltd.

Nova Scotia	Owner
Prince	Cape Breton Development Corp
Phalen	Cape Breton Development Corp

Minor Mines (Natural Resources Canada 1998)

Alberta	Nova Scotia
Dodds	Stellarton
Egg Lake	Thomas Brogan
	Evans
	Thorbourn

Table 3. List of coal-based electrical generating stations (by province)

Generating station	Ownership	Generating station	Ownership
Alberta	Owner	Ontario	Owner
Sundance	TransAlta Utilities Corporation	Nanticoke	Ontario Hydro
Wabamun	"	Lakeview	"
Keephills	"	Lambton	"
Battle River	Alberta Power Ltd.	Thunder Bay	"
H. R. Milner	"	Atikokan	"
Sheerness	" + TransAlta Utilities Corporation		
Genesee	Edmonton Power		
Saskatchewan	Owner	New Brunswick	Owner
Boundary Dam	Saskpower	Belledune	N. B. Power
Poplar River	"	Dalhousie	"
Shand	"	Grand Lake	"
Manitoba	Owner	Nova Scotia	Owner
Brandon	Manitoba Hydro	Lingan	N. S. Power
Selkirk	"	Glace Bay	"
		Point Alconi	"
		Trenton	"
		Point Tupper	"

Table 4. Thallium concentrations, ng/L, in waters from western coal mines

Western Mines	Site / Sample Description	Tl Concentration
Whitewood Mine (TransAlta Utility Corp)	Pit Water Discharge (some black deposit, clear decantate), decanted	6.64
Highvale Mine (Manalta Coal)	Pit 2 Drain (brown deposit , ~ clear dark brown decantate), decanted	463.6
	" duplicate, centrifuged	518.5
	Pit 3 (some brown deposit, ~ clear dark brown decantate), decanted	106.9
	" duplicate, centrifuged	109.3
	Beaver Creek (clear)	2.92
	Pit 3 Settling Pond - Outflow (clear)	0.32
	Pit 3 Settling Pond - Inflow (black deposit, clear d br decantate), decanted	846.1
	" duplicate, centrifuged	1326.2
	Well Water (local groundwater) (vis partics, clear decantate), decanted	5.47
Genesee Mine	Mine Drainage (some brown deposit, clear decantate), decanted	7.52
Coal Valley Mine	Tailings Discharge (vis particulates, clear decantate), decanted	7.20
Luscar - Sterco (Luscar Ltd)	Lovett River Intake (clear)	2.82
	" duplicate	2.43
	Coal Creek Impoundment (clear)	2.70
	Lovett River d/s (clear)	8.64
	" duplicate	4.21
	25 ? East mine drain (vis particulates, clear decantate), decanted	16.4
	Centre Creek (treated water) (clear)	16.6
	Reservoir (well water) (clear)	1.74
Gregg River Mine (Manalta Coal)	HI Pit - Plant make up (clear)	16.3
	Plant Site Water Reservoir (clear)	63.9
	Refuse = Tailings (Black coal-like deposit, clear decantate !), decanted	9.49
	Well Water - tap (clear)	3.67
Cardinal River Mine (Luscar Ltd)	West Jarvis Creek Intake (clear)	4.13
	Luscar Creek d/s Plant (vis particulates, clear decantate)	6.54
	" duplicate, decanted	5.92
Cardinal River Mine (Luscar Ltd)	Tailings (Black coal-like deposit, clear decantate), decanted	17.1
	Well Water (clear)	1.46
	Luscar Creek, d/s Cardinal & Gregg Mines (clear)	3.56
Whitehorse Creek	At Mountain Park (clear)	1.78
	d/s Mountain Park (clear)	1.33
	d/s Cadomin (abandoned, but active quarry) (clear)	2.39
Gregg River	d/s Gregg River Mine (at Hwy 40) (clear)	2.59
Obed Mountain Coal (Luscar Ltd)	E. Conveyor Settling Pond (vis particulates, clear decantate), decanted	3.61
	Main Tailings Pond (Lower) (vis particulates, clear decantate), decanted	0.91
	Reservoir (treated water) (vis particulates, clear decantate), decanted	7.97
	Main Tailings Pond (Upper) (dark brown deposit, clear decantate), decante	2.24
	" duplicate, decanted	2.95
	LSP2 - Coal Storage Drain (for rail shipment) (clear)	19.1
Smoky River Coal (Smoky River Coal)	Sheep Creek u/s Smoky River (clear)	2.42
Line Creek Mine (Manalta Coal)	Settling Pond Discharge MSA North Ponds (clear)	5.26
	Line Creek u/s - 0200335 (clear)	0.66
	" duplicate	0.20
	South Pit Water (dark brown deposit, clear decantate), decanted	217.4
	Line Creek d/s (clear)	6.92
	" duplicate	5.37
	Wash Water after Thickener (vis particulates, clear decantate), decanted	38.5
	Tap Water Not Treated (clear)	9.07
Elk River	At Sparwood d/s from four mines (clear)	2.51
Crowsnest Creek	Crowsnest Pass (d/s coal mountain mine) (clear)	9.09
Sheerness Mine (Luscar Ltd)	Pit Water (visible particulates, light decantate), decanted	10.6

Table 4. Continued

Western Mines	Site / Sample Description	Tl Concentration
Montgomery Mine	Pit Water (visible particulates, light decantate), decanted	1.84
(Manalta Coal)	Settling Pond Discharge (visible particulates, light decantate), decanted	4.55
Carolside Reservoir	d/s mines and G.S.'s (visible particulates, light decantate), decanted	4.19
Paintearth Mine	Surface Runoff Discharge (very brown, brown decantate), decanted	811.2
(Luscar Ltd)	Section 7 Lake (pit & surface runoff) (d. brown, light brown decantate), de	63.0
	Impoundment #5 Discharge (black deposit, v. brown decantate), decanted	1119.1
	Paintearth Creek d/s (Very brown deposit, light brown decantate), decanted	257.3
	Paintearth Creek u/s (Brown deposit, very light brown decantate), decanted	35.7
	Blank before	0.73
	Blank after	0.93
Vesta Mine	North Drainage (Brown deposit, very light brown decantate), decanted	53.5
(Manalta Coal)	Vesta East - Pond 3 (Brown deposit, clear decantate), decanted	51.7
Crowsnest River	u/s Chinook Coal PlantColeman, Alberta (clear)	4.29
(Chinook coal)	(decommissioned in 1978) (clear)	4.72
(Manalta Coal)	Blank before (clear)	0.14
	Blank after (clear)	0.72
	d/s Chinook Coal Plant (clear)	3.96
	" duplicate	4.72
	d/s Coleman & Frank Slide (clear)	5.07
	d/s Leitch Colliery (clear)	2.95
Hell's Gate	Groundwater (clear)	2.58
Athabasca River	Hwy. 93 South of Jasper (clear)	1.03
Poplar River North Mine	Settling Pond NSP1 (clear)	2.81
(Prairie Coal Ltd.)	u/s East Poplar River (clear)	0.92
	" duplicate	1.19
	East Poplar River - Upstream Blank (clear)	0
	" duplicate	0
	East Poplar River - Downstream (clear)	3.79
Utility Mine (Prairie Coal Ltd.	Settling Pond E-4	34.9
	Pond near coal storage pile	6.86
	Dewatering Discharge into BD Reservoir	8.05
Boundary Dam Mine (Estervan Coal Corporation)	Settling Pond / Holding Pond	17.7
Bienfait Mine (Estervan Coal	Dewatering Discharge from west side of mine	50.7
Corporation)	Discharge from Mine areas of section 4-2-6-W2M (V-notch weir)	12.8
Costello Mine Expansion (Prairie Coal Ltd)	Dewatering Discharge from proposed mine	1.26
Old Mac Mine - abandoned	Old Coal Spoil Pond (Old Mac Mine)	0.31
Quinsam Mine	Blank before (clear)	1.13
(Quinsam Coal Corporation)	Blank after (clear)	0.19
	on Quinsam River flowing towards mine (clear)	0.14
	" duplicate	0.68
	Settling pond (clear)	5.69
	" duplicate	6.27
	d/s from the mine on Quinsam river before going into the small lake (clear)	0.35
	" duplicate	0.53
	d/s outlet of the small lake (clear)	1.47
	" duplicate	1.07

Notes:
"Decanted" refers to 20ml pipetted from the top of bottle, which has been let settle in the cold room for overnight or longer
"Centrifuged" refers to sample being centrifuged as compared to decanted
"Visible particulates" are particulates at bottom of bottle
d/s = downstream
u/s = upstream

Table 5. Thallium concentrations, ng/L, in waters from eastern coal mines

Eastern Mines	Site / Sample Description	Tl Concentration
8200 Salmon Harbour Mine	Pit Water (visible particulates, clear decantate), decanted	53.3
(NB Coal)	" duplicate, decanted	35.2
	Lagoon Discharge (visible particulates, clear decantate), decanted	9.33
	" duplicate, decanted	6.55
	Lake Water (visible particulates, clear decantate), decanted	7.72
	" duplicate, decanted	7.43
Phalen Colliery, NS	Mine Water Discharge (high Na) (brown clear decantate), decanted	424.0
(Cape Breton Developmt Corp)	Town Water (from tap at security) (clear)	4.13
	Surface Runoff Brook (visible particulates, clear decantate), decanted	169.2
Victoria Junction Coal	V.J. Tailings Basin Old Final Discharge KL1 (clear)	18.9
Preparation Plant, NS	V.J. Tailings Basin KL3 (clear)	1.47
(Cape Breton Developmt Corp)	V.J. Final Discharge WWT3 (treated water) (clear)	121.1
	North and South Process Wells (for wash & town w) (clear)	0.64
	Surface water Pond WWT1 (brown, clear brown decantate), decanted	404.3
Prince Colliery, NS	Process Water (reservoir and well combined) (clear)	1.95
(Cape Breton Developmt Corp)	Mine Discharge and Coal Pile Runoff (light clear decantate), decanted	698.3
	Treated Lagoon Discharge (clear)	565.0
	d/s Discharge (clear)	552.5
	" duplicate	514.0
Abandoned coal mines*:		
Gardiner Mine	Mine Discharge (clear brown decantate)	0.15
Pioneer Coal	at Sydney Airport	100.9
"	" duplicate	107.2
Brogan Brothers	at Pt. Aconi 5th seep	83.8
"	at Pt. Aconi 11th seep	76.5
Prince	at Edwards Pond	660.6
"	" duplicate	718.5

Notes:
"Decanted" refers to 20ml pipetted from the top of bottle, which has been let settle in the cold room for overnight or longer
"Centrifuged" refers to sample being centrifuged as compared to decanted
"Visible particulates" are particulates at bottom of bottle
d/s = downstream
u/s = upstream
(high salt ?) = probably the sample contains high salt content as it has to be diluted to be analyzable.
Particulates in decantate may result in high results if decantate is not diluted; filtration or digestion may be needed for more accurate results if dilution is not done.
* Samples were thankfully subsampled by Mr. Henry Wong

Table 6. Thallium concentrations, ng/L, in waters from western generating stations (G S = Coal-fired electrical generating sation)

Western GSs	Site / Sample Description	Tl Concentration
Wabamun G S	Intake Water (clear)	0.15
(TransAlta Utility Corpora	" duplicate	0.61
	Blank before (clear)	0.90
	Blank after (clear)	0.05
	Ash Lagoon Effluent (clear)	5.87
	" duplicate	4.57
	Ash slurry (some black deposit, clear decantate), decanted	8.44
	" duplicate, centrifuged	11.4
	Discharge Water (clear)	2.53
Wabamun Lake	At Wabamun d/s Wabamun GS (clear)	1.78
Sundance G S	North Saskatchewan River Intake (clear)	2.27
(TransAlta Utility Corpora	" duplicate	2.01
	Blank before (clear)	1.02
	Blank after (clear)	0.27
	Pond discharge (clear)	5.83
Keephills GS	River Make Up (clear)	1.40
(TransAlta Utility Corpora	" duplicate	3.29
	Blank (clear)	0.04
	Cooling Pond Discharge (clear)	4.32
	" duplicate	4.36
	Ash Recirculation Water (clear)	8.46
	Ash Lagoon Slurry (some black deposit, clear decantate), decanted	140.2
	" duplicate	150.6
Genesee GS	Intake Water (clear)	7.27
(Edmonton Power)	" duplicate	7.06
	Blank before (clear)	3.97
	Blank after (clear)	1.32
	Discharge Water (clear)	15.1
	" duplicate	12.4
North Saskatchewan River	d/s Keephills and Sundance G.S. (clear)	15.1
H.R. Milner GS	Waste Water - Discharge (visible particulates, clear decantate), decanted	9.25
(Alberta Power Ltd)	Smoky River Intake (clear)	1.15
	Final Discharge (visible particulates, clear light br. decantate), decanted	4.09
	" duplicate	6.90
	" duplicate, centrifuged	2.26
H.R. Milner GS	Smoky River d/s Discharge (clear)	2.69
Smoky River	u/s Sheep Creek (clear)	3.17
	" duplicate	2.89
	u/s H.R. Milner G.S. at Hwy. 40 (clear)	1.89
	" duplicate	3.40
	Blank before (clear)	0.03
	Blank after (clear)	0.01
Sheerness GS	Intake Water (visible particulates, clear decantate), decanted	5.13
(Alberta Power Ltd)	Discharge Water (visible particulates, clear decantate), decanted	8.30
	" duplicate, decanted	8.65
	" duplicate, centrifuged	17.5
	" duplicate, centrifuged	8.41
	Cooling Water Lagoon (clear)	9.47
	" duplicate	6.43

Table 6. continued

Western GSs	Site / Sample Description	Tl Concentration
Battle River GS	Battle River u/s (visible particulates, clear decantate), decanted	7.87
(Alberta Power Ltd)	" duplicate, decantated	7.11
	Intake Water (visible particulates, clear decantate), decanted	1.81
	Ash Lagoon - Input (some black deposit, clear decantate), decanted	37.9
	Ash Lagoon - Discharge (some dark deposit, clear decantate), decanted	18.6
	Discharge Water (visible particulates, clear decantate), decanted	6.64
	" duplicate, decanted	2.62
	Spillway d/s (visible particulates, clear decantate), decanted	14.1
	Battle River d/s (clear)	3.53
	" duplicate	6.68
	Blank before (clear)	2.46
	Blank after (clear)	5.78
Boundary Dam GS	Spoil Pond 5-5 (SERM Station no. 72579) (clear)	36.2
(Saskpower)	Spoil Pond 32-5 (SERM Station no. 72524) (clear)	30.5
	Long Creek inlet (BDC1 - SERM208)- u/s Boundary Dam Reservoir (clear)	3.12
	Cooling Water inlet (BDC2 - SERM72506) (clear)	21.5
	Cooling Water Discharge Canal: Return to Reservoir (BDC1 - SERM44886)	24.7
	Long Creek below Boundary Dam Reservoir (BDC3 - SERM235) (clear)	97.5
	u/s Souris River near Boundary Dam GS (clear)	4.48
	", duplicate (clear)	2.98
	", Blank before (clear)	0.04
	", Blank after (clear)	0.11
	d/s Souris River @ Nopney's crossing	1.54
Poplar River GS	Auxilary Cooling Water (ACW) canal discharging to Cookson Reservoir	0.19
(Saskpower)	d/s East Poplar River (SERM 541)	5.21
Shand GS (Zero discharge (Saskpower)	Raw water sample	35.7
Estevan GS (inactive)	Discharge into drainage ditch no. 7	65.0
(Saskpower)	Ash lagoon no. 5 (SE corner)	6.32
Selkirk GS	Red River Intake	16.5
(Manitoba Hydro)	Well Intake	15.7
	Selkirk Discharge	63.9

Notes:
"Decanted" refers to 20ml pipetted from the top of bottle, which has been let settle in the cold room for overnight or longer
"Centrifuged" refers to sample being centrifuged as compared to decanted
"Visible particulates" are particulates at bottom of bottle
d/s = downstream
u/s = upstream

Table 7. Thallium concentrations, ng/L, in waters from eastern and central (Ontario) generating stations (G S = Coal-fired electrical generating sation)

Eastern and Ontario	Site / Sample Description	Tl Concentration
*Belldune G.S.	Coal Pile Runoff (Brown - black deposit, clear decantate), decanted	744.1
(NB Power)	Equalization Pit (plant waters) (dark deposit, clear decantate), decanted	2376.6
	Treated Discharge (visible particulates, clear decantate), decanted	4000.5
	Ash Leachate Pond Discharge (clear)	5087.1
Grand Lake GS	Ash Lagoon Discharge (clear)	11989.0
(NB Power)	" duplicate	11453.0
	Lake (visible particulates, clear decantate), decanted	159.1
	Intake Water (visible particulates, clear decantate), decanted	25.4
	" duplicate, decanted	23.3
Lingan GS	Ash Lagoon Return (visible particulates, clear decantate), decanted	4426.1
(NS Power)	Waste Water Discharge to Lagoon (black deposit, clear decantate), decanted	885.4
	Pretreatment Waste Water (vis black deposit, clear decantate), decanted	2660.0
	Coal Pile Runoff (visible particulates, clear yellowish decantate), decanted	417.5
Point Aconi GS	Ash Leachate Pond Discharge (pH 12) (clear)	398.1
(NS Power)	Coal Pile Runoff (visible particulates, clear brownish decantate), decanted	569.2
	Waste Water Discharge (Lingan sample #96-150) (clear)	558.0
	Well Water (Intake water) (clear)	0.53
Point Tupper GS	Waste Water - pretreatment (visible particulates, clear decantate), decanted	33.7
(NS Power)	Coal Berm Runoff Pond (brown - yellow clear, clear decantate), decanted	212.1
	Final Wastewater Discharge - treated (clear)	373.6
	Landrie Lake Water (visible particulates, clear decantate), decanted	1.94
	Ash Leachate Pond Discharge (clear)	1034.6
Trenton GS	Coal Leachate Pond (visible particulates, clear decantate), decanted	1076.0
(NS Power)	Ash Lagoon Discharge (clear)	23605.0
	Intake Water (treated town water) (clear)	0.86
	Pit B Discharge (previously collected by Trenton) (clear)	982.0
Lambton Hydro GS	Coal Pile Runoff Creek @ Sarnia	55.6
(Ontario Hydro)	" duplicate	70.3
	Water Intake channel @ Sarnia	3.18
	" duplicate	3.18
Lakewiew GS	Intake Channel @Toronto	6.06
(Ontario Hydro)	North Coal Runoff Pond	112.1
	Blank @Toronto	0.00
	Ash Lagoon Filtration Effluent @Toronto	175.3
Nanticoke GS	Outfall Channel	18.2
(Ontario Hydro)	Intake Channel	11.8
	Ash Lagoon	41.5
	Coal Pile Runoff Pond	50.1
Antikokan GS	Intake line	1.25
(Ontario Hydro)	Discharge/Sn. Lake	28.1
Thunder Bay GS	Intake canal	7.16
(Ontario Hydro)	Discharge canal	14.0
	d/s Mission River	9.39

Notes:
* Belledune GS uses 75% Columbian coal and 25% Salmon Harbor Mine coal
"Decanted" refers to 20ml pipetted from the top of bottle, which has been let settle in the cold room for overnight or longer
"Visible particulates" are particulates at bottom of bottle
Particulates in decantate may result in very high results if decantate is not diluted; filtration or digestion may be needed for more accurate results if dilution is not done.

Table 8. Canadian coal-based electrical generation capacity, megawatts

G Stations	Owner	Total Capacity, MW
Sundance	TransAlta Utilities Corp.	1987
Wabamun	TransAlta Utilities Corp.	569
Keephills	TransAlta Utilities Corp.	754
Battle River	Alberta Power Ltd.	735
H. R. Milner	Alberta Power Ltd.	140
Sheerness	Alberta Power Ltd. and TransAlta Utilities Corp.	766
Genesee	Edmonton Power	400
Boundary Dam	SaskPower	875
Poplar River	SaskPower	592
Shand	SaskPower	272
Brandon	Manitoba Hydro	237
Selkirk	Manitoba Hydro	132
Thunder Bay	Ontario Hydro	423
Nanticoke	Ontario Hydro	4096
Lakeview	Ontario Hydro	2400
Lambton	Ontario Hydro	2040
Atikokan	Ontario Hydro	230
Belledune	N. B. Power	440
Dalhousie	N. B. Power	286
Grand Lake	N. B. Power	82
Lingan	Nova Scotia Power	602
Glace Bay	Nova Scotia Power	116
Trenton	Nova Scotia Power	350
Point Aconi	Nova Scotia Power	165
Point Tupper	Nova Scotia Power	150

Table 9. Concentrations of heavy metals in sediments

Sample Site	Site / Sample Description	Tl* ug/g	Hg* ug/g	Co ug/g	Cr ug/g	Cu ug/g	Fe %	Mn ug/g	Pb ug/g	Ni ug/g	Zn ug/g
Wabamun GS, Alberta	Intake Water	0.52		17.5	57.9	28.8	2.1	742	<2.5	28.8	68.1
"	Ash Lagoon Effluent	0.43		9.7	39.9	20.3	1.7	180	<2.5	18.4	46.2
Sundance GS, Alberta	Ash Slurry	0.99		13.1	17.4	45.1	1.7	343	34.5	19.4	33.4
Keephills GS, Alberta	Cooling Pond Screen Waste	0.69		9.9	56.6	35.2	2.1	303	<2.5	27.7	108.0
"	Ash Lagoon Slurry	0.35		13.5	21.9	28.3	2.1	348	<2.5	19.2	18.6
"	Ash Lagoon Cenospheres	1.20		6.2	9.0	39.4	1.2	87	31.4	13.7	19.5
Genesee GS, Alberta	Discharge	0.52		10.2	47.2	36.4	2.4	573	<2.5	21.9	95.1
Smoky River, Alberta	u/s Sheep Creek, 5km d/s HR Milner	0.39		7.8	35.7	19.2	1.7	221	<2.5	25.5	70.9
"	u/s H.R. Milner G.S. at Hwy. 40	0.34		8.9	40.3	19.3	1.6	208	3.7	17.0	68.4
Battle River GS, Alberta	Battle River u/s	0.36	0.04	5.3	28.4	8.6	1.6	297	<2.5	15.3	42.8
"	Battle River d/s	0.47	0.04	3.3	22.3	4.9	1.2	280	<2.5	10.2	28.6
Grand Lake GS, NB	Lake	0.78	0.02	5.9	23.2	8.2	2.4	688	<2.5	12.5	34.5
Trenton GS, Nova Scotia	Ash Lagoon Cenospheres	0.89		20.7	55.2	77.3	2.6	164	86.1	44.5	156.0
Souris River, Saskatchewan	u/s Estevan, mines and gs	0.68	0.11	15.0	89.8	35.9	3.6	464	<2.5	43.1	115.0
"	u/s Estevan, mines and gs	0.68	0.10	11.7	76.0	32.7	3.2	430	<2.5	34.8	99.9
"	d/s Estevan, mines and gs	0.49	0.06	8.1	55.3	21.1	2.2	319	<2.5	21.6	73.5
"	d/s Estevan, mines and gs	0.45	0.07	7.8	56.3	22.5	1.9	289	<2.5	20.5	67.6
Bienfait Mine, Saskatchewan	Pit Water Discharge	0.54		8.0	36.5	16.7	1.2	284	11.0	13.0	76.1
Whitewood Mine, Alberta	Pit Water Discharge	0.47		7.4	36.5	25.8	1.5	258	5.0	16.3	158.0
Highvale Mine, Alberta	Pit 2 Drain	0.87		19.0	69.5	54.3	2.5	378	<2.5	42.5	98.1
"	Pit 3 Settling Pond - Outflow	0.62		18.1	76.9	44.4	3.2	398	<2.5	38.4	94.9
Genesee Mine, Alberta	Mine Drainage	1.04		17.1	77.7	54.6	3.1	369	<2.5	39.6	170.0
Coal Valley Mine, Alberta	Tailings Discharge	0.47		15.3	60.7	32.9	2.6	448	<2.5	33.8	94.7
"	Lovett River d/s	0.59		12.9	80.0	25.9	2.4	906	<2.5	33.5	82.8
Gregg River Mine, Alberta	Plant Site Water Reservoir	0.52		16.8	44.8	54.3	1.1	339	8.5	37.0	196.0
Obed Mountain Coal, Alberta	E. Conveyor Settling Pond	0.25		8.7	39.1	24.7	1.4	417	7.7	20.3	68.4
"	Main Tailings Pond (Upper)	3.39		8.1	16.6	14.8	2.9	318	33.8	9.5	105.0
"	LSP2 - Coal Storage Drain	0.42		4.7	23.8	17.5	1.0	194	10.2	11.9	59.3
Line Creek Mine, BC	Settling Pond	1.11		7.4	52.4	31.5	0.9	153	9.5	22.9	199.0
8200 Salmon Harbour Mine, NB	Lake Water	0.74	0.05	26.7	94.3	36.8	5.8	1972	<2.5	45.1	132.6
Phalen Colliery, Nova Scotia	Surface Runoff Brook	1.25	0.06	21.3	39.9	30.8	**17.0**	640	54.5	37.6	126.0
Prince Colliery, Nova Scotia	d/s Discharge	0.61	0.06	11.5	53.7	24.7	3.7	614	12.9	31.0	109.3

* Tl was determined by LEAFS, Hg by CVAAS, other metals by ICPAES

Table 10. Comparison of sediment guideline levels* with some high levels of metals found in some sites

	Cd µg/g	Cr µg/g	Fe %	Mn µg/g	Pb µg/g	Ni µg/g	Zn µg/g
Lowest effect level*	0.6	26	2	460	31	16	120
Severe effect level*	10	110	4	1100	250	75	820
Marginally-significantly polluted*	0.6 -10	26 - 110	2 - 4	460 - 1100	31 - 250	16 - 75	120 - 820
Phalen Colliery sediment	16.2	39.9	17	640	54.5	37.6	126
Salmon Harbor Mine sediment	<3.4	94.3	5.8	1972	<2.5	45	133
Trenton GS sediment	<3.4	55.2	2.6	164	86	45	156
Prince Colliery sediment	<3.4	53.7	3.7	614	12.9	31	109

* The guidelines defines 3 levels -- no effect level, lowest effect level, and severe effect level (Jaagumagi and Persaud 1995). Below the "no effect level", the sediment quality is termed "**clean**", i.e. no impact on water quality, water uses or benthic organisms is anticipated. Between the "no effect level" and "lowest effect level", the sediment quality is termed "**clean-marginally polluted**", i.e. the sediment has a potential to affect some sensitive water uses. Between the "lowest effect level" and the "severe effect level", the sediment quality is termed "**marginally-significantly polluted**", i.e. some benthic organisms will be affected. Above the "severe effect level", the sediment quality is termed "**grossly polluted**", i.e. benthic organisms will be significantly affected by the use of the sediment.

Table 11. Concentrations, ng/g, of the 16 priority PAHs and benzo[e]pyrene and perylene

		*Sample #	28S	34S	105S	128S	**141S	209S dup1	209S dup2	211S dup1	211S dup2
		Weight (g)	41.82	59.81	43.23	19.31	28.08	12.89	12.97	38.59	29.98
		Final Vol (ml)	1	1	1	1	1	1	1	1	1
COMPOUND	M/z										
NAPHTHALENE	128		13	2	11	704	4059	61	74	18	14
ACENAPHTHYLENE	152		2	0.2	ND	13	359	26	8	1	1
ACENAPHTHENE	154		1	ND	ND	8	602	7	6	1	0.8
FLUORENE	166		2	0.3	0.4	36	756	105	12	6	3
PHENANTHRENE	178		9	2	5	326	3399	68	89	18	10
ANTHRACENE	178		1	ND	ND	NC	739	NC	NC	4	1
FLUORANTHENE	202		5	1	1	32	385	262	380	14	11
PYRENE	202		6	1	7	67	599	222	298	20	17
BENZO[a]ANTHRACENE	228		2	0.4	ND	19	156	69	83	3	3
CHRYSENE	228		4	0.8	1	59	131	142	218	7	6
BENZO[b]FLUORANTHENE	252		5	2	ND	26	22	103	137	7	6
BENZO[k]FLUORANTHENE	252		2	0.4	ND	5	5	36	44	2	2
BENZO[a]PYRENE	252		2	0.7	ND	14	28	30	32	2	1
INDENO[1,2,3-cd]PYRENE	276		ND	ND	ND	ND	ND	ND	ND	ND	ND
DIBENZ[a,h]ANTHRACENE	278		ND	ND	ND	ND	ND	ND	ND	ND	ND
BENZO[ghi]PERYLENE	276		ND	ND	ND	ND	ND	ND	ND	ND	ND
TOTAL (ng/g)			54	10.8	25.4	1309	11240	1131	1381	103	76
BENZO[e]PYRENE (ng/g)	252		2	0.6	ND	29	16	40	55	2	1
PERYLENE (ng/g)	252		26	9	ND	ND	2	16	20	9	7

* Sample 28S = Battle river upstream; 34S = Battle river downstream; 105S = Grand Lake GS; 128S = Salmon Harbor mine; 141S = Prince colliery downstream discharge; 209S = Souris river upstream; 211S = Souri river downstream

** Results obtained after silica gel fractionation and sulfur clean-up. Unusually high Anthracene concentration (also high in samples 209sdup1 and dup2)

ND = not detected; NC = not confirmed

Table 12. Concentrations, µg/g, of n-alkanes in sediment samples

*Sample #		28S	34S	105S	128S	**141S	209S dup1	209S dup2	211S dup1	211S dup2
Weight (g)		41.82	59.81	43.23	19.31	28.08	12.89	12.97	38.59	29.98
Final Vol (ml)		1	1	1	1	1	1	1	1	1
COMPOUND	C-No.	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g
n-C12	12	0.01	ND	ND	0.09	1.49	0.03	0.04	0.04	0.03
n-C13	13	0.02	ND	ND	0.09	1.74	0.04	0.05	0.03	0.03
n-C14	14	0.02	ND	ND	0.09	2.77	0.10	0.12	0.05	0.04
n-C15	15	0.03	0.01	0.01	0.09	1.10	0.20	0.23	0.08	0.06
n-C16	16	0.03	0.01	0.01	0.09	2.06	0.24	0.27	0.11	0.06
n-C17	17	0.17	0.04	0.02	0.15	2.11	0.92	1.21	0.28	0.19
n-C18	18	0.06	0.03	0.02	0.15	1.40	0.86	0.75	0.36	0.25
n-C19	19	0.08	0.04	0.03	0.21	1.87	1.09	0.86	0.41	0.32
n-C20	20	0.48	0.02	0.04	0.24	3.06	0.94	0.77	0.30	0.30
n-C21	21	0.08	0.02	0.04	0.25	2.31	0.96	0.53	0.03	0.29
n-C22	22	0.06	0.02	0.03	0.15	2.32	0.36	0.33	0.17	0.16
n-C23	23	0.19	0.06	0.01	0.15	2.28	0.42	0.39	0.46	0.39
n-C24	24	0.08	0.03	0.01	0.07	3.16	0.20	0.24	0.20	0.16
n-C25	25	0.06	0.03	0.01	0.31	1.89	0.53	0.66	0.67	0.55
n-C26	26	0.11	0.04	ND	0.07	2.22	0.26	0.29	0.21	0.18
TOTAL (ug/g)		1.48	0.35	0.22	2.20	31.77	7.14	6.72	3.39	3.01
Carbon Preference Index (Mean CPI = 1.3 ± 0.3)		0.8	1.5	1.1	1.4	0.8	1.5	1.5	1.5	1.7

* Sample 28S = Battle river upstream; 34S = Battle river downstream; 105S = Grand Lake GS; 128S = Salmon Harbor mine; 141S = Prince colliery downstream discharge; 209S = Souris river upstream; 211S = Souri river downstream

** Results obtained after silica gel fractionation and sulfur clean-up

ND = not detected

Table 13. Survival, growth, and reproduction of *Chironomus riparius, Hexagenia spp., Hyalella azteca,* and *Tubifex tubifex* in sediments

	Chironomus riparius		*Hexagenia spp.*		*Hyalella azteca*		*Tubifex tubifex*			
	% Survival	Growth, mg	% Survival	Growth, mg	% Survival	Growth, mg	% Survival	# Cocoons/Adult	% Hatched	# Young/Adult
Reference Values*										
Non toxic	>69	0.21 - 0.49	>85	1.0 - 5.0	>68	0.24 - 0.76	>88	7.2 - 12.3	40 - 78	12.0 - 45.6
Potentially toxic	60 - 68.9	0.14 - 0.20	80 - 84.9	0 - 0.9	58 - 67.9	0.11 - 0.23	84 - 87.9	5.9 - 7.1	30.8 - 39.9	3.6 - 11.9
Toxic	<60	<0.14	<80	--	<58	<0.11	<84	<5.9	<30.8	<3.6
Sediment Site**										
Souris River - U/S	80.0	0.31	97.5	3.89	93.3	0.50	100	8.9	57.4	23.7
Souris River - D/S	89.3	0.32	98	4.29	89.3	0.64	100	8.5	**27.8**	13.1
Battle River G. S.	**16.0**	0.27	100	4.54	**68**	0.38	**87.5**	**5.2**	62.5	**5.7**
Prince Colliery	**40.0**	0.38	94	1.34	**36.7**	**0.10**	95	8.7	59.6	33.9
Salmon Harbour Mine	**66.7**	0.45	90	6.32	80	0.41	---	---	---	---

* Reynoldson et al. 1997.
** U/S = upstream; D/S = downstream; G. S. = coal-based electrical generating station
Note: --- Salmon Harbour not suitable for *T. tubifex* test due to large number of endemic worms.

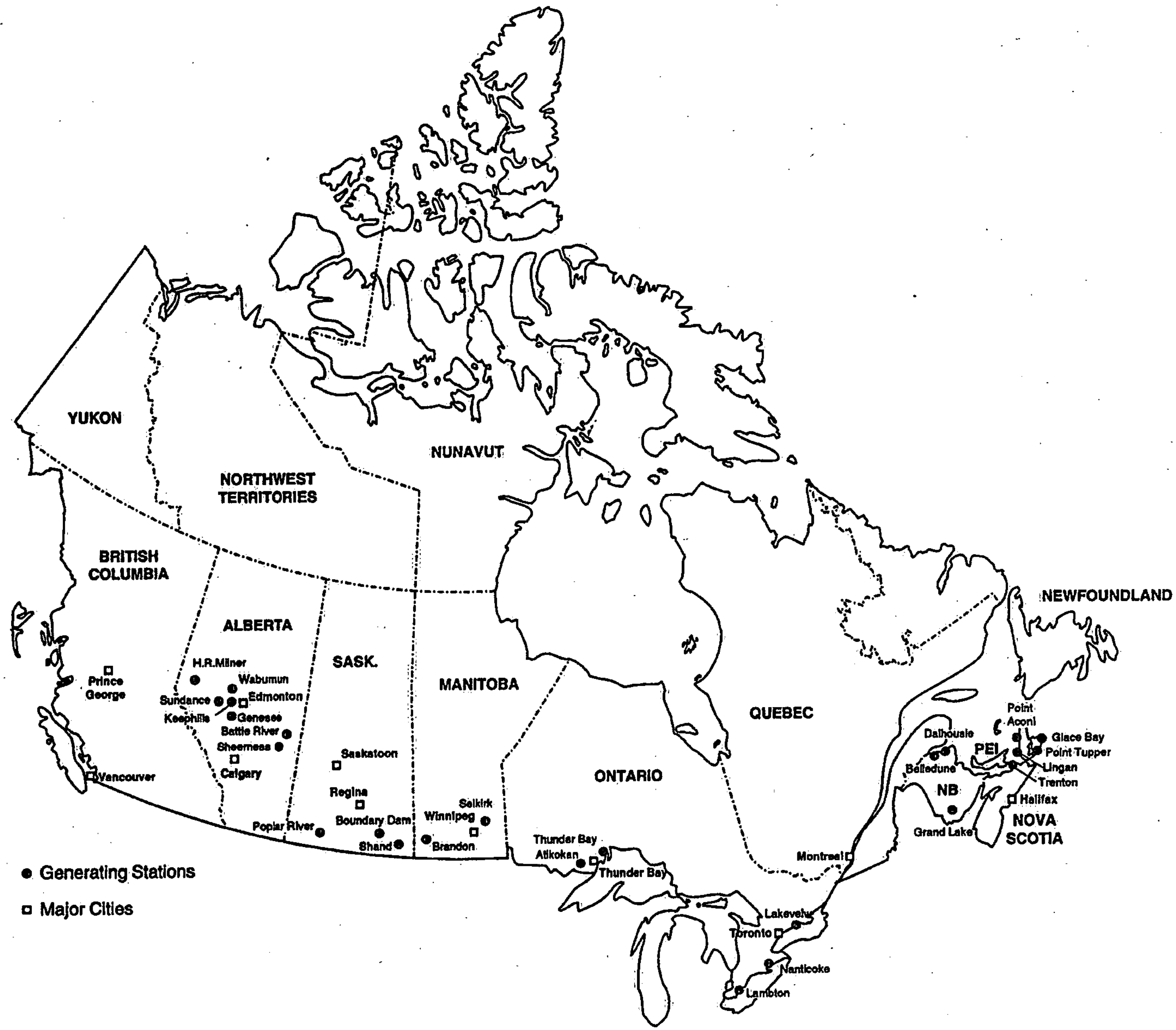

Fig. 1. Coal-fired electrical generating stations in Canada.

Fig. 2. Principal coal mines in Canada.

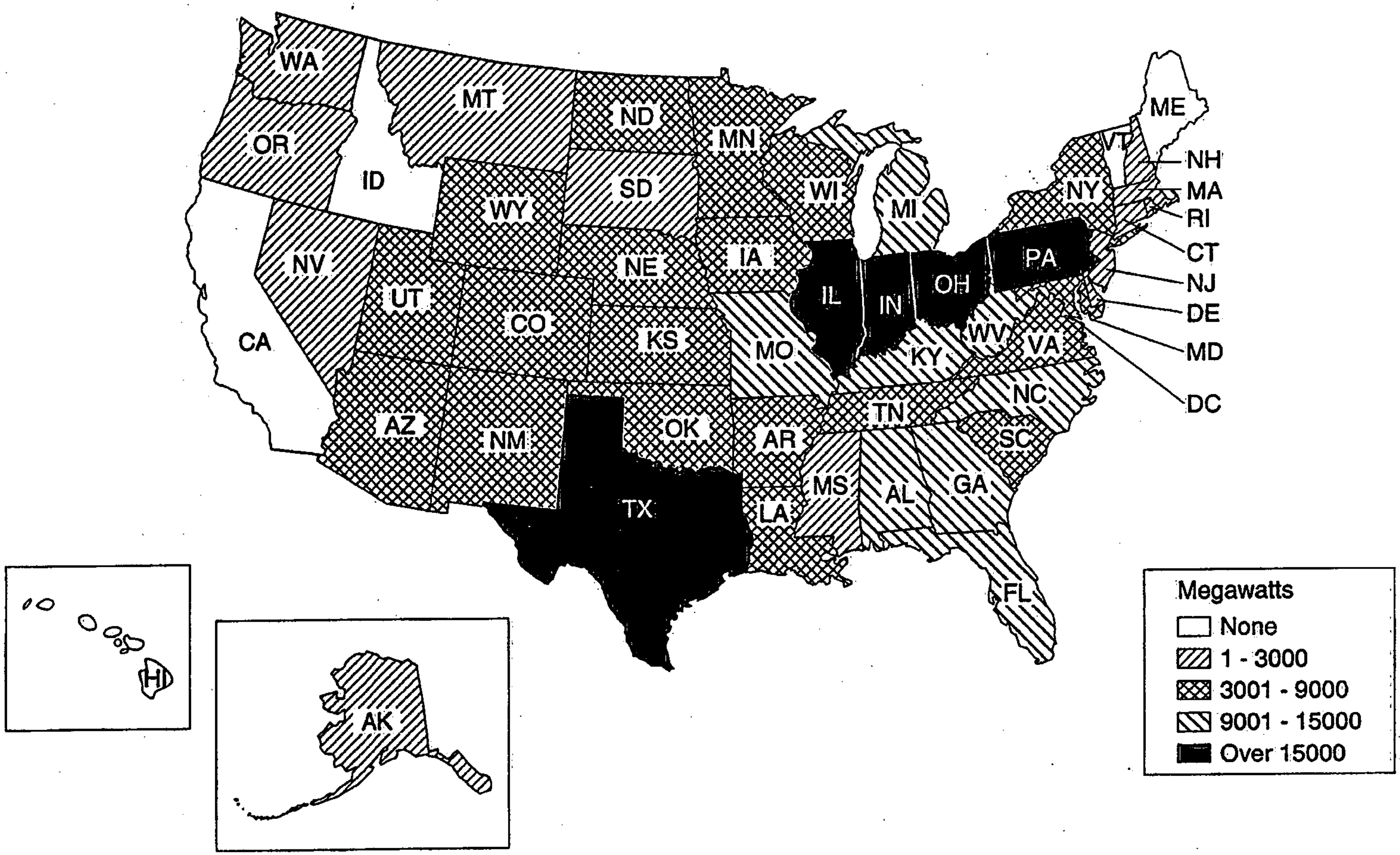

Fig. 3. Coal-fired generating capacity by state in USA (as of December 31, 1993)

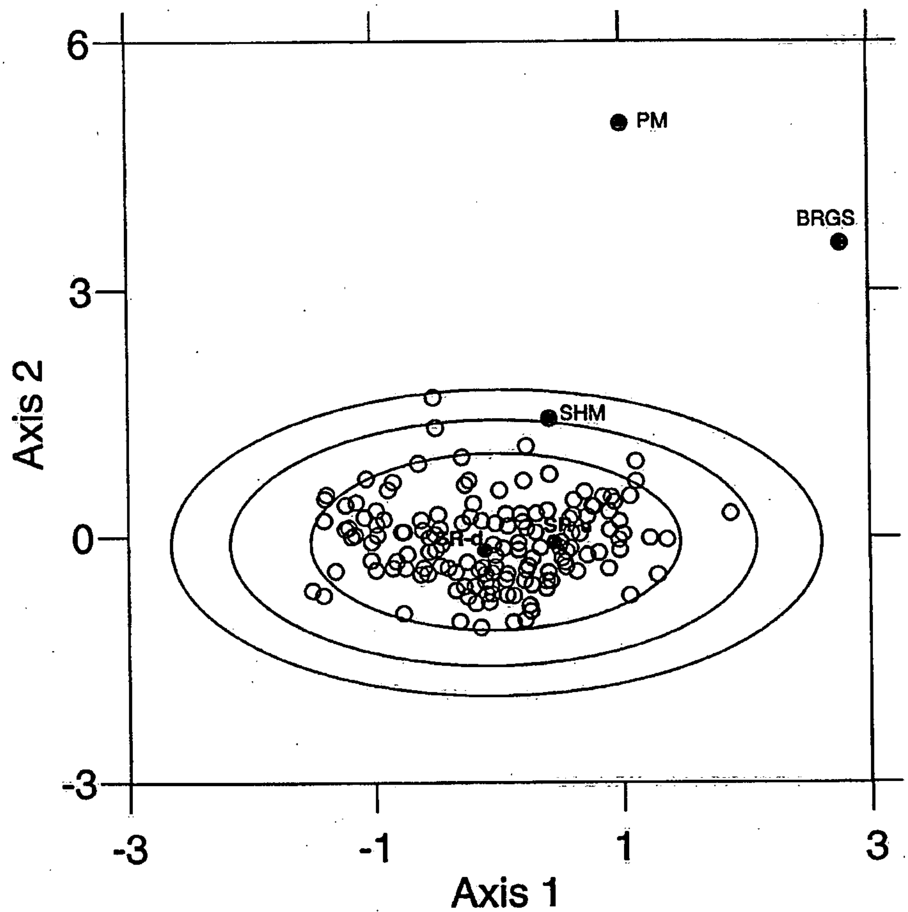

Fig. 4. Assessment of sediment toxicity by ordination of six bioassay endpoints (BRGS = Battle River generating station; PM = Prince mine; SR-U and -D = Souris River upstream and downstream; SHM + Salmon Harbour mine.

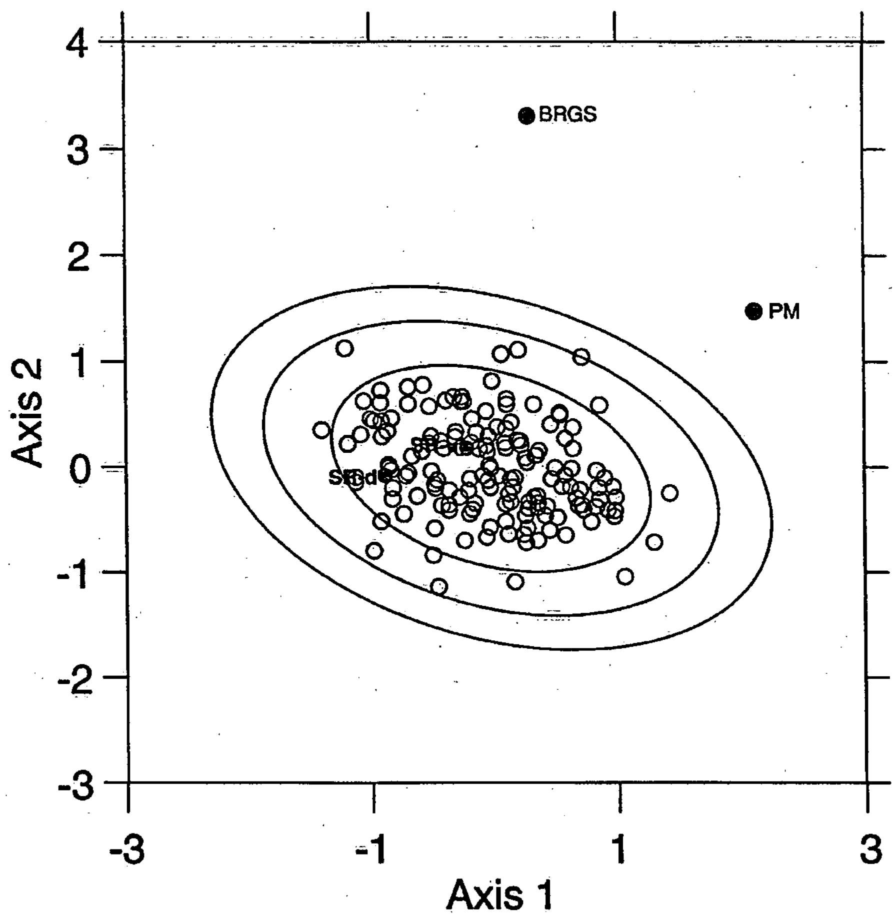

Fig. 5. Assessment of sediment toxicity by ordination of ten bioassay endpoints (BRGS = Battle River generating station; PM = Prince mine; SR-U and -D = Souris river upstream and downstream).

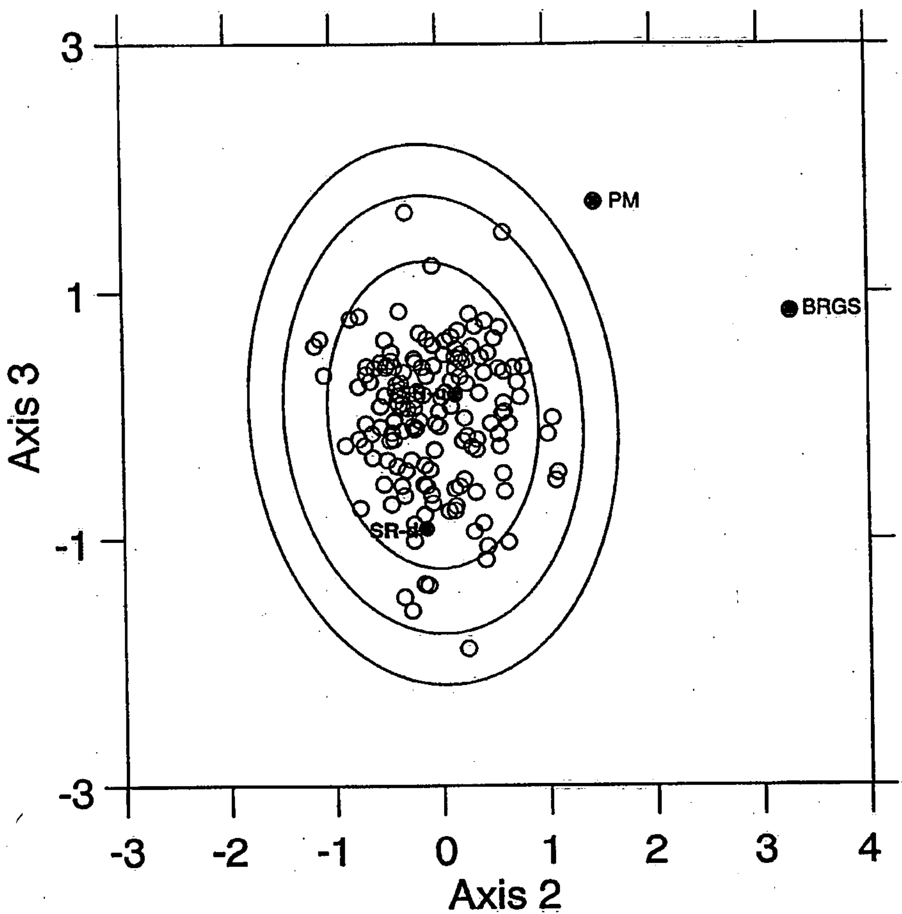

Fig. 6. Assessment of sediment toxicity by ordination of ten bioassay endpoints (BRGS = Battle River generating station; PM = Prince mine; SR-U and -D = Souris River upstream and downstream).

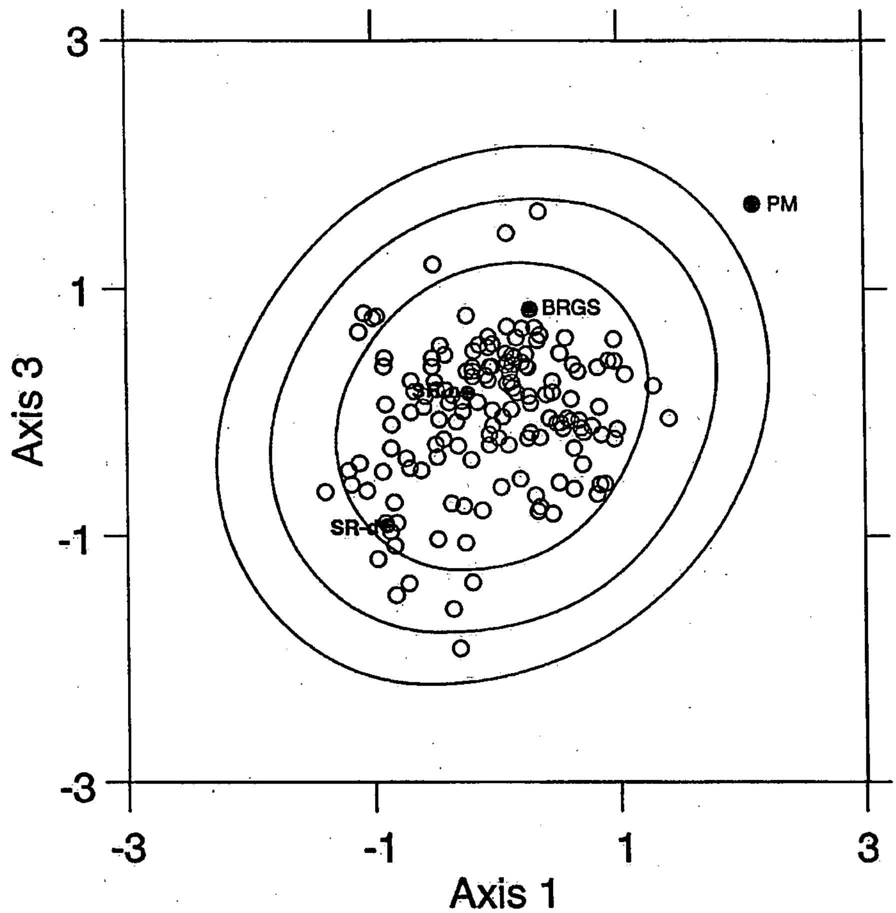

Fig. 7. Assessment of sediment toxicity by ordination of ten bioassay endpoints (BRGS = Battle River generating stations; PM = Prince mine; SR-U and -D = Souris River upstream and downstream.

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