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Technical Communication

Heavy Metal Pollution Assessment in Surface Water Bodies and its Suitability for Irrigation around the Neyevli Lignite Mines and Associated Industrial Complex, Tamil Nadu, India

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Abstract. Opencast lignite mines, pit-head thermal power plants, and other associated industries in the Neyveli mining and industrial complex generate huge quantities of solid and liquid wastes that are contaminated with heavy metals. Some of these are toxic or carcinogenic at sufficient concentrations. Copper, Zn, Mn, Fe, Ni, Cd, Cr, Co, Pb, and Hg concentrations in surface water in the study area are from 2 to 1200 times higher than average concentrations in river water worldwide. Heavy metal contamination in the natural reservoirs (Peria, Kolakudi, Walaza, and Perumal Ponds, and the Paravannar River) is mainly due to the discharge of untreated mine water, fly-ash pond water, and effluents from associated industries. These waters have long been used for bathing, washing, animal watering, etc. Untreated mine and industrial waste water, and natural reservoir water have been used by nearby villagers for irrigation for the last four decades, which may have led to deterioration of soils, surface water, and groundwater. Heavy metal analyses of mine water, fly-ash pond and industrial effluents and the natural reservoirs reveals that Co, Cr, and Hg are above the recommended irrigation water quality standards in 17%, 75%, and 100% of the samples, respectively. Most samples were within the permissible limits for Mn, Ni, and Fe, while Pb, Zn, Cd, and Cu were within the limits in all samples. At elevated concentrations, toxic metals like Cr, Co, and Hg can accumulate in soils and enter the food chain, leading to serious health hazards and threatening the long-term sustainability of the local ecosystem.

Key Words: Fly ash; heavy metals; irrigation; lignite; Neyveli; opencast mines; Tamil Nadu; thermal power plants; wastewater

Introduction

The contamination of aquatic and terrestrial ecosystems with heavy metals is a major environmental problem. Some of these metals are potentially toxic or carcinogenic at sufficient concentrations and can cause serious human health hazards if they enter the food chain. Investigations have been made of the extent of heavy metal pollution of surface water, groundwater, soils, air and vegetation by mining and associated industrial activities, particularly thermal power plants and opencast coal mines (Allan 1988; Benvenuti et al. 1997; Caruccio 1972; Coulthard et al. 2003; Fang et al. 2003; Gulec et al. 2001; Hansen and Fisher 1980; Kabata-Pendias 1995; Klein et al. 1975; Lee 1975; Liorens et al. 2001; Mohanty et al. 2001; Rupper et al. 1996; Sahu 1998; Sen et al. 1996; Swaine 1990). Metal pollution by mining and associated industrial activities is somewhat mitigated today by strict implementation of clean technology and environmental measures. However, metals released previously by such activities have been retained in the sediments and soils, and still contaminate surface and ground water resources.

We examined an area that includes two very large (Mines I and II) and one small (Mine IA) opencast lignite mines, associated industries (two pit-head thermal power plants, a urea plant, and a briquetting and carbonization plant) that are operated by Neyveli Lignite Corporation Ltd. (NLC), and an independent power plant. Initially, in 1962, NLC had one captive opencast mine with a capacity of 3.5 MT/y linked to a 50 MW capacity pit-head thermal power station (TPS I). Since then, with the growing demand for electricity, lignite production and power-generation capacity has increased tremendously. Currently, NLC is mining 10.39 MT/y (Mine I), 8.70 MT/y (Mine II), and 1.46 MT/y (Mine IA) of lignite linked to 600 MW (TPS-I) and 1470 MW (TPS-II) capacity thermal power plants. The independent power plant, with a capacity of 250 MW, has not yet been activated. Furthermore, the Indian government has sanctioned the expansion of Mines I and II from 6.5 to 10.5 MT and 10.5 to 15 MT and the expansion of TPS-I and TPS-II from 600 to 1020 MW and 1470 to 1970 MW, respectively.

However, the production of urea (fertilizer plant) and coke (briquetting and carbonization plant) has declined from 0.152 (1966) to 0.062 MT (2002) and 0.436 (1965) to 0.004 MT (2002), respectively. These activities previously generated huge quantities of solid and liquid wastes that were indiscriminately dumped and drained into natural reservoirs and agricultural land.

Solid wastes included overburden mine waste, fly ash dumped from thermal power plants, and wastes from the briquetting and carbonization plant. About 1250 MCM of overburden has been removed since inception (1957) from Mine I, which is currently removing 70 MCM/Y. Mine II has removed a total of 700 MCM of overburden since inception (1982) and is presently removing 61 MCM/Y. The power plants (TPS-I, 600 MW and TPS-II, 1417 MW) consume about 10,000 and 85,000 T/d of lignite, and 45,500 and 386,000 L/min of water respectively. As a result, TPS-I and TPS-II produce approximately 3300 and 11650 T/d of fly ash as a by-product. Thus, the dumping of fly ash, overburden, mine and industrial waste, and the discharge of mine water, fly-ash pond water, and associated industrial effluents pose major environmental challenges for both mining engineers and environmental scientists. Every MW generating capacity of power plant requires 1 ha of land for ash disposal (Murty 1996).

Generally, about 550,000 L/min of water are pumped from the pits in a normal season, though much more is pumped during monsoons. Huge quantities of untreated wastewater are also discharged from fly-ash ponds and associated industries into natural reservoirs (Peria, Kolakudi, Walaza and Perumal Ponds, and Paravannar River) and agricultural fields. The water in the ponds and river is severely contaminated with heavy metals, but has been used for the last several decades by nearby villages for irrigation, animal watering, bathing, and washing, etc. Today, about 8,100 ha of agricultural land are irrigated by wastewater discharged from the mine pits and associated industries. Thus, even though the lignite mining, thermal power plants and associated industries have been operating under some form of environmental control, the reservoirs receive an influx of potentially toxic metals from them. To our knowledge, no work has been done on the heavy metal contamination of surface-water bodies caused by the mining, power plants and associated industries in and around the Neyveli mine–industrial complex. This study assessed the level of heavy metal contamination in the surface-water bodies, its distribution and sources, and possible risk connected with the use of this water for agricultural irrigation.

Description of Study Area

The Neyveli mine-industrial complex is located in the Cuddalore District, Tamil Nadu, India (Figure 1). The area has a tropical climate with the highest and lowest temperatures recorded in June (43.3^{0}C) and January (10.4^{0}C), respectively. At the mine site, the average annual precipitation is 1369 mm with 55% and 45% rainfall from the NE and SW monsoons, respectively.

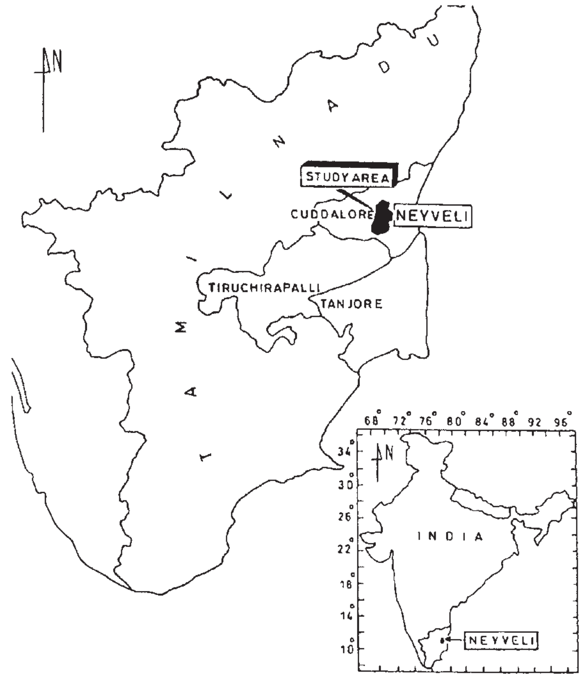

Figure 1. Location map of the study area

The area gently slopes southeast and east, and is not drained by any major river except for a small ephemeral stream (the Paravannar River) flowing east. This carries mine water and industrial effluent instead of natural water, and discharges into the Walaza and Perumal Ponds east of the lignite mines.

The study area is underlain by the Tertiary Cuddalore Formation and by Recent alluvium. The Cuddalore sandstones cover mostly the north and west areas and the alluvium mostly the east and southeast areas of the Neyveli lignite region. The lignite occurs in the Cuddalore formation at depths ranging from 45 to 120 m below ground level (bgl).

The hydrogeology of the Neyveli Groundwater basin is extremely complex, consisting of a series of productive confined aquifers below the lignite seam in both the Mine I and II areas, while a semi-confined aquifer lies above the seam and occurs only in the Mine II area. In the Cuddalore sandstones, groundwater occurs in unconfined, semi-confined, and confined conditions, while in the alluvium it occurs in an unconfined condition. In the study area, both the Tertiary Cuddalore Formation and the Recent alluvium form a potential aquifer system.

Lignite Mining

Lignite is mined by the opencast method, using a bucket wheel excavator, conveyors, and spreader. Annual production is shown in Figure 2. Figure 3 presents average annual pumping of mine water and groundwater from Mine I.

The Cuddalore sandstones and Recent alluvium form the principal overburden waste material, together with small amounts of clays (fire clay and white clay). Details of average overburden removal are given in Figure 4. The sandstones are very hard, compact, and abrasive in nature. According to NLC (Balasundar 1968), the average chemical composition of the Cuddalore sandstones is: SiO_2 (76%), Al_2O_3 (14.5%), Fe_2O_3+FeO (4.25%), CaO (0.5%), MgO (1%), NaO_2 (Trace), and TiO_2 (Trace).

Marcasite (FeS_2) occurs in various forms in the lignite, sandstones and aquifer sands. It is difficult to separate marcasite from lignite because of its non-magnetic character and sporadic occurrences. It causes damage to excavating machinery because of its hardness, and also causes ash melting, sintering, slagging, etc. in the power plants. Marcasite oxidizes when it comes in contact with the atmosphere during mining. Pumping of groundwater then releases significant amounts of metals (Powell 1988).

Power plants at Neyveli produce approximately 500 M^3 of fly ash per day and its disposal is a major challenge to plant engineers. Moreover, fly ash tends to adsorb and often contains various metals (Pb, Hg, Cr, Mn, Cu, Co, Ni, Cd, Zn, etc.), some of which are very toxic and/or carcinogenic.

Materials and Methods

Twenty-eight representative surface-water samples were collected from mine sumps and effluents power-plant reservoirs and effluents, fly-ash ponds, natural ponds and the river in the vicinity of the Neyevli mine industrial complex. Sampling was carried out in Feb. 2003 using standard techniques (APHA 1995). Sampling stations are shown in Figure 5. Water samples were collected in sterile 1 L polyethylene bottles and after being filtered (pore size=0.45µm), each sample was treated with 10 ml HNO_3 to prevent possible precipitation of heavy metals.

The water samples were analyzed for heavy metals according to international standard methods (APHA 1995). The analyses of Cu, Fe, Cr, Mn, Ni and Co were performed in the Dept of Geology, A.M.U., Aligarh, using Atomic Absorption Spectrophotometer (AAS) (Perkin-Elmer, Aanalyst 800). The Pb, Hg, and Cd analyses were done in the Toxicology and Environmental Lab, Dept. of Medical Elementology and Toxicology, Hamdard University, New Delhi, using AAS (Analytic Xena Zeenit 65). In the heavy metal analysis by AAS, quality control was monitored using 10% sample blanks and 10% sample replicates in each set of sample analyses.

Results and Discussion

The heavy metal concentrations in various surface water samples collected in the vicinity of the mine-industrial complex are given in Table 1. Certain trends

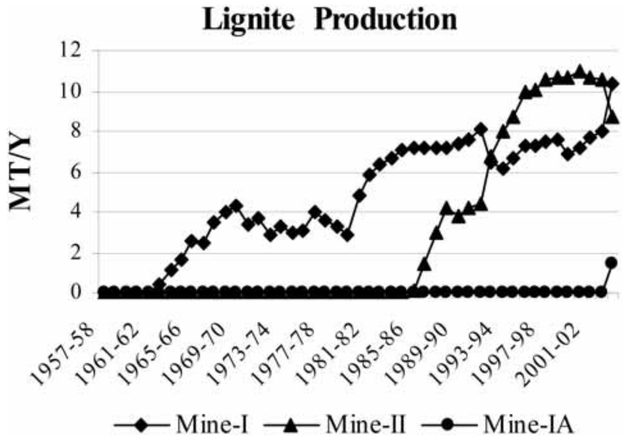

Figure 2. Average annual lignite production

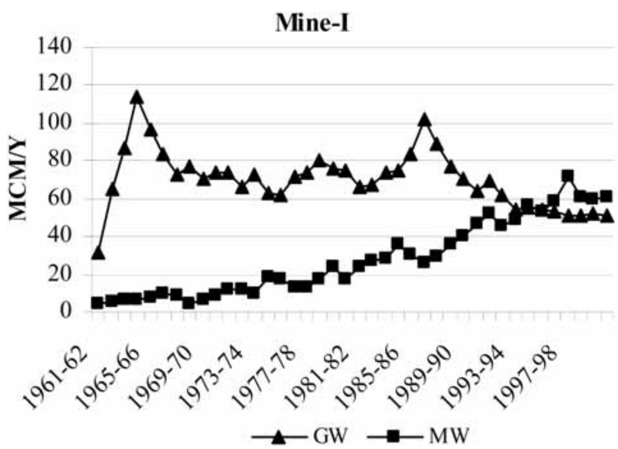

Figure 3. Annual pumping of groundwater (GW) and mine water (MW) from Mine I

Figure 4. Total annual removal of overburden

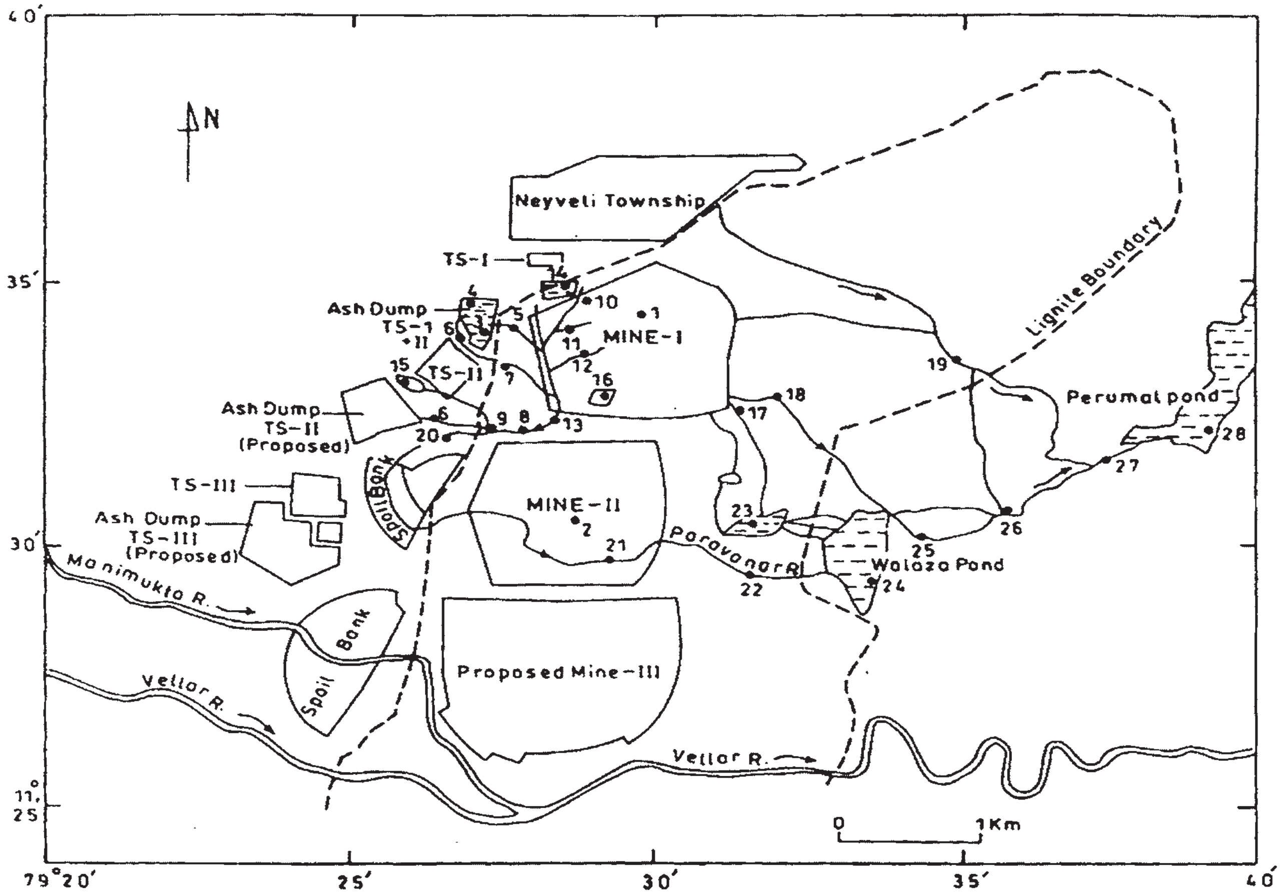

Figure 5. Schematic diagram of surface water flow from the lignite mining and industrial complex and location of sampling sites

should be noted. Samples taken directly from the fly-ash slurry pipe had higher metal concentrations than samples taken after settling in the fly-ash pond. Thus, a significant amount of toxic metals had been absorbed by the fly ash. Nevertheless, the wastewater released from the fly-ash ponds and mine pits that discharge into natural reservoirs still had elevated metal concentrations. The lowest concentrations were recorded at Perumal Pond, which is located 13 km from the mining activities. The heavy metal concentrations in Paravannar River decrease downstream, except for iron at a few places. Furthermore, the concentrations of heavy metals in other surface water bodies located near the complex are higher than in those located further away.

In summary, the highest total metal levels in the study area were in water samples collected directly from the slurry pipe at fly-ash pond-II, followed by fly-ash pond-II water (after settling) and in mine water; the lowest were in Perumal Pond. The lignite, fly-ash disposal at ash ponds, overburden mine waste, mine water, oxidation of marcasite and emission of toxic metals from the power plants are considered the principal geochemical sources of heavy metal pollution in the study area.

Heavy Metal Pollution Assessment

Wastewater from the mine pits, fly-ash ponds and various industries are discharged without prior treatment into natural reservoirs (Kolakudi, Walaza and Perumal Ponds, and Paravannar River) and agricultural fields, resulting in serious metal contamination in surface-water, soil, and groundwater. We assessed the extent of heavy-metal contamination in surface-water bodies by comparing concentration ranges and mean values recorded in the study area with the average metal content of the world's rivers (Taylor and McLennan 1985) (Table 2). The mean value of Cu, Zn, Mn, Fe, Ni, Cd, Cr, Co, Pb, and Hg in the investigated area are respectively 2, 6, 17, 75.5, 200, 260, 275, 350, 484, and 1200 times higher than the average levels in the world's rivers. The Fe, Cr, Co, Ni, Pb, Mn, and Hg in all of the surface water bodies exceeded the average levels in the world's rivers.

Almost all of the metal concentrations in pond water exceeded the averages in the world's rivers, but the metal content in pond water overall was relatively less than in the other surface water bodies. The high concentration of Fe was mainly due to oxidation of marcasite and ferruginous sandstones, but Fe is much

Table 1. Heavy metal concentrations in surface-water bodies around the Neyveli lignite mine-industrial complex (Feb., 2003); all values in mg/L

Sample	Location	Fe	Pb	Zn	Cr	Co	Ni	Mn	Cd	Cu	Hg
MW-1	Mine-I	2.493	0.881	0.067	0.316	0.146	0.049	0.039	0.004	0.02	0.063
MW-2	Mine-II	2.103	0.69	0.039	0.297	0.112	0.05	0.049	0.003	0.039	0.071
FE-3	Flyash pond-II(slurry pipe)	29.36	1.476	0.944	0.946	0.158	0.236	0.37	0.009	0.039	0.278
FE-4	Flyash pond-II(after settling)	2.528	1.132	0.05	0.267	0.52	0.087	0.031	0.007	0.014	0.154
FE-5	Overflow flyash pond-II(east)	1.353	0.478	0.043	0.107	0.026	0.068	0.022	0.004	0.01	0.125
FE-6	Overflow flyash pond-II(west)	1.638	1.049	0.044	0.113	0.033	0.083	0.073	0.005	0.014	0.115
FE-7	Near TPS-II	1.813	0.091	0.041	0.406	0.018	0.071	0.078	0.004	0.022	0.101
FE-8	Vadakuvellur	1.222	0.493	0.069	0.49	0.024	0.062	0.253	0.003	0.023	0.033
FE-9	Umangalam	1.714	0.398	0.033	0.443	0.048	0.076	0.143	0.004	0.003	0.03
TE-10	B-point(near mine-I)	3.666	0.497	0.032	0.405	0.009	0.024	0.469	0.002	0.015	0.037
MW-11	Near lignite yard	0.411	0.39	0.057	0.043	0.005	0.036	0.036	0.003	0.009	0.328
MW-12	Thoppilekkuppam	4.055	0.488	0.075	0.295	0.007	0.013	0.08	0.003	0.011	0.206
ME-13	Mandarkuppam	4.968	0.81	0.089	0.396	0.022	0.087	0.115	0.001	0.019	0.154
PW-14	TPS-I(reservoir water)	1.23	0.231	0.015	0.033	0.004	0.024	0.102	0.002	0.005	0.029
PW-15	TPS-II(reservoir water)	1.601	0.69	0.017	0.426	0.025	0.065	0.02	0.003	0.018	0.028
PW-16	Peria Pond	0.212	0.612	0.258	0.161	0.005	0.026	0.019	BDL	0.017	0.025
MW-17	Periyakkurichi	2.186	0.468	0.052	0.281	0.023	0.034	0.058	0.002	0.014	0.086
MW-18	Near Seplanatham	2.546	0.31	0.09	0.433	0.018	0.031	0.088	BDL	0.013	0.053
MW-19	Veenankeni	2.609	0.437	1.058	0.412	0.132	0.153	0.403	0.002	0.029	0.048
ME-20	Near pump house	3.017	0.403	0.068	0.249	0.021	0.08	0.167	0.001	0.011	0.098
ME-21	Karuvatti	3.48	0.213	0.04	0.094	0.013	0.049	0.084	0.001	0.004	0.042
ME-22	Turinjikollai	2.032	0.19	0.034	0.106	0.011	0.031	0.084	0.002	0.002	0.031
PW-23	Kolakundi Pond	0.681	0.11	0.028	0.014	0.02	0.038	0.083	0.001	0.014	0.044
PW-24	Walaja Pond	3.89	0.71	0.072	0.435	0.018	0.058	0.199	0.003	0.028	0.038
ME-25	Karamedu	2.634	0.39	0.044	0.382	0.016	0.043	0.132	0.001	0.011	0.03
ME-26	Paravanar Bridge	0.419	0.19	0.049	0.084	0.019	0.053	0.043	0.001	0.011	0.029
ME-27	Aduragram Bridge	0.379	0.084	0.041	0.048	0.013	0.043	0.036	0.001	0.01	0.029
ME-28	Perumal Pond	0.338	0.063	0.037	0.021	0.009	0.034	0.031	0.001	0.009	0.025

MW=mine water, FE=fly ash effluent, TE=thermal power plant effluent, PW=pond water, ME=mixed effluent

Table 2. Average and range of heavy metals in surface water bodies around the Neyveli mine-industrial complex compared with the average in the world's rivers (Taylor and McLennan 1985) and irrigation water quality standards (FAO 1985; WHO 1989); all values in mg/L

Elements	World River Water (Avg)	Irrigation Water standards	Study Area: Ranges for all surface water bodies in area	Study Area: Ranges for pond water in the area	Study Area: Average
Fe	0.04	5	29.36-0.338	3.89-0.212	3.02
Pb	0.001	5	1.476-0.063	0.71-0.063	0.484
Zn	0.02	2	0.944-0.015	0.258-0.028	0.124
Cr	0.001	0.1	0.946-0.014	0.435-0.014	0.275
Co	0.0001	0.05	0.150-0.004	0.02-0.005	0.35
Ni	0.0003	0.2	0.236-0.013	0.058-0.026	0.06
Mn	0.007	0.2	0.490-0.012	0.199-0.019	0.12
Cd	0.00001	0.01	0.009-BDL	0.003-BDL	0.0026
Cu	0.007	0.2	0.038-0.003	0.028-0.009	0.015
Hg	0.00007	0.01	0.328-0.025	0.044-0.026	0.084

less toxic than some of the other metals. Pb concentrations were above the average levels in the world's rivers. Elevated concentrations of Cr in the area are mainly due to lignite, fly-ash dumps from thermal power plants, and mine water. The burning of coal alone discharges 3000 T of Cr annually into the environment (Taylor et al. 1979). Cd concentrations in the majority of the samples were equivalent to the average of the world's river water, except at Periyakkurichi and Veenankeni. The highest concentrations of Zn, Ni, Co, and Cu were in fly-ash pond water, and the lowest in the TPS-I reservoir water. The Zn concentrations in the majority of samples were above the average for the world's rivers, except for the TPS-I and TPS-II reservoirs. In the case of Cu, all but four samples showed concentrations below the average of the world's rivers.

Suitability for Irrigation

Currently, about 550,000 L/min of water is pumped from the mines pits in a normal season, with much higher quantities going into natural reservoirs such as Kolakudi, Walaz and Perumal Ponds and the Paravannar River during the monsoon period. Furthermore, huge quantities of water enter the reservoirs through drainage channels from the fly-ash ponds and other industries. For the last four decades, this wastewater has been discharged into the reservoirs without any treatment and then used for irrigation, bathing, washing and animal watering. In such conditions, toxic elements often accumulate in the soil and may gradually pass into edible parts of crops and into the food chain, posing considerable health risks to human and animals (Pillay et al. 2003). Before the opening of Mine II in 1985, about 2400 ha of land were being irrigated by surplus water from Mine I alone. At present, NLC plans to irrigate about 8000 ha of land by surplus water from the lignite mines (>www.nlcindia.com<).

The deficiency or excess of certain trace elements in irrigation water can retard growth and metabolic activities. Hence, neither the nutrient value nor the toxicity of trace elements in irrigation water can be ignored. Wastewaters discharged from the lignite mine pits, fly-ash ponds and associated industries, and water from Kolakudi, Walaza and Perumal Ponds, and Paravannar River were compared with the maximum permissible limits of heavy metals for Irrigation Water Quality Standards (FAO 1985; WHO 1989). Table 2 reveals that the average concentrations of Hg (0.084 mg/L) and Cr (0.275 mg/L) exceeded the recommended limits whereas Pb, Mn, Ni, Co, Zn, Cu, Cd, and Fe were well within the permissible limits. Hg is a neurotoxin that accumulates in the food chain and can damage the brain, spinal cord, kidneys, liver and is also hazardous to developing fetuses. Hg in all samples was above the recommended limits (Hg=0.01 mg/L). Cr can also be highly toxic, depending on its valence state. The Cr concentrations in 75% of the samples were above the maximum acceptable limit.

The Co concentrations at FE-3, MW-1 (Co=0.146 mg/L), MW-19 (Co=0.132 mg/L), MW-2 (Co=0.112 mg/L), and FE-4 (Co=0.052 mg/L) were above the maximum acceptable limit (Co=0.05 mg/L) whereas other samples were within the recommended limits. Only one sample showed Ni concentrations above the permissible limits. The Mn concentrations in two samples were above the recommended limits. In the case of Fe, only one sample had a concentration above the recommended limit. However, Zn, Pb, Cd, and Cu concentrations in the surface-water bodies were well within the maximum acceptable limit established for irrigation water quality. The Fe, Pb, Mn. Co, Ni, Cd, Cu, and Zn concentrations were in compliance with the irrigation standards, while Hg and Cr were above the recommended limits.

Conclusions

Elevated concentration of heavy metals (i.e. Pb, Cr, Hg, Cd, Fe, Cu, Ni, Co, Zn and Mn) were recorded in untreated wastewater discharged from mine pits, fly-ash ponds and industrial effluents in the vicinity of the Neyveli mines-industrial complex. This untreated wastewater drains into natural reservoirs (Kolakudi, Walaza and Perumal Ponds and Paravannar River), resulting in concentrations several times higher than average world river water values. It not only pollutes surface-water bodies but also contaminates groundwater resources to the east and southeast of the Neyveli mines-industrial area.

Wastewater discharged from the lignite mine-industrial complex and water from the natural reservoirs has been used for irrigation by nearby villages for four decades. This study reveals that some of the more toxic metals (Hg, Cr, and Co) exceed the maximum acceptable limits for irrigation. Irrigation using this metal-loaded wastewater may not only pollute the soils but could also be allowing toxic metals to enter into the food chain, posing a serious health hazard. Long-term utilization of this untreated wastewater for irrigation is presumed to be unhealthy for the local environmental ecosystem. Given the planned expansion of the operations in the area, the environmental risks will increase if remedial measures are not taken to proper manage and treat the wastewater before it is discharged into natural reservoirs and agricultural fields.

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