



ASPECTS OF WASTE MANAGEMENT AND POLLUTION CONTROL IN OLKARIA GEOTHERMAL FIELD, KENYA

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ABSTRACT

The Olkaria geothermal field, located within the Hell's Gate national park in the eastern branch of the African rift system in Kenya, has been under exploitation for over 20 years. The greatest environmental challenge has been the large volume of waste geothermal fluids and effluents generated during the exploration and utilisation processes. In this paper the results of an attempt to characterize geothermal and associated waste materials and emissions in terms of their origin, quantity, chemical content, and environmental behaviour, are presented. The basic principles and waste management criteria for the categories identified are reviewed. Closely related aspects of pollution control in the Olkaria region through a monitoring programme for geothermal chemical components and trace elements of environmental significance that arise from the geothermal wastes (Zn, Cd, Pb, Cu, Li, Ba, and F), are described. The results indicate that concentration levels of trace elements Zn, Cd, Cu and Ba in geothermal well discharge water, wastewater, effluents, and condensates are below the international health optimum limits which is not the case for Pb, Li and F. The concentration levels of all the elements except F in potable water sources in the vicinity of the exploited area are within acceptable limits. Soil and vegetation show a small enrichment in the elements but the levels are still far below limits above which contamination is declared.

Sound management is needed of the geothermal waste fluids and effluents through reinjection and constructed "wetland" systems, periodic monitoring of element levels and studies of impact indicators. Drilling mud, sludge, scales and other construction and maintenance debris must be disposed of in properly designed and managed landfills. Similarly, careful storage and handling of toxic and hazardous dosing chemicals and petroleum products is needed. Thus, the potentially negative environmental effects can be made negligible.

1. INTRODUCTION

Waste is any substance or object which the holder discards, intends or is required to discard by provisions of national law (Bodry, 1991). These may be exploration, production or consumption

residues, unusable parts, and contaminated materials. The holder, in this case, is the producer of the waste or the natural or legal person who is in possession of it.

As is common with other energy development processes, geothermal energy resource exploration and utilization result in the generation of solid waste residues and discharges through gas, steam, bore and cooling water. Some of these wastes have been reported to contain chemical components and trace elements at concentration levels above normal soils, water, and atmospheric air. The potential environmental impacts, particularly on human health, domestic animals, and wildlife which may arise from geothermal chemical contaminants, are of major concern.

There has been a growing global environmental awareness, and in response governments all over the world have introduced legislation with an aim to protect the environment and human health. More so, regional and international bilateral energy projects funding agencies and institutions such as the World Bank, have also included operational directives on environmental impact assessment (EIA) with similar objectives. Therefore, adherence to national and international environmental regulations and/or directives, statutes or laws is of paramount importance to various industries for any development to be environmentally sustainable. The geothermal energy producing industry is no exception.

Careful management that entails collection, transport, recovery, storage and disposal of waste, including the supervision of such operations and after-care of disposal sites, is of major significance in environmental management to minimise or even eliminate the impacts from geothermal waste residues and emissions. In addition, the practise of using designed pollution control criteria which involve monitoring programmes for environmental significant chemical contaminants is essential. The monitoring programmes should be able to provide useful and defensible scientific data and information to determine the status of affected environmental resources, to predict future effects, and enable the management of geothermal industry to decide on possible mitigating measures against observed and predicted impacts considered unacceptable.

In this report, a relatively broad consideration is accorded to the general aspects of waste management and pollution control in geothermal resource exploration and utilization. The main objectives are to characterize and classify in terms of origin, quantity, chemical content and environmental behaviour categories of the geothermal and associated wastes; review conventional waste management and pollution control criteria for prevention or minimization of possible adverse effects on human health and the environment that could arise from geothermal chemical contaminants; and analyse data acquired from pollution monitoring programmes for environmental significant chemical components and trace elements in Olkaria geothermal field, Kenya.

2. LITERATURE REVIEW

Due to the significance of environmental implications for energy development, a comparative overview of the waste scenario in different energy sources: nuclear, fossil fuel, hydro power, solar, wind, tidal, and geothermal, is essential.

The problem of waste is universal in the development of global energy resources. However, the physical and chemical nature of the waste, environmental impacts of the contaminants, and the management and disposal criteria in use vary depending on the type of energy source exploited.

In the case of nuclear energy, estimates from the International Atomic Energy Agency (IAEA) show that by the end of 1992 about 135, 000 Megagrams of spent nuclear fuel had been produced (Dormuth et al., 1995). The spent nuclear fuel contains plutonium (Pu) and uranium (U) and is not necessarily a waste as it can be recycled back into the reactors to produce more energy. Thus, spent or waste nuclear fuel

is radioactive and generates waste heat. However, the volume of waste per unit of electricity generated is small.

If the spent nuclear fuel is reprocessed as is done at facilities in France, India, Japan, Russia, and the United Kingdom, a solid waste form, such as borosilicate glass, is manufactured to incorporate most of the unwanted radioactive material and this would be managed and disposed in much the same way as spent fuel. The environmental implications of the disposal processes are global due to the trans-boundary movement of such wastes.

The potential effects of radioactive elements, if swallowed or inhaled can be hazardous and include fatal cancer or serious genetic defects. Hence the need for elaborate management and disposal of the nuclear wastes through isolated storage in either water-filled pools (wet storage) or in metal or concrete structures filled with inert gas or air; disposal by removal from the earth by transporting it into space; transmutations which entail changing some of the radioactive elements in the waste to different elements by nuclear methods in order to reduce the long-term radiotoxicity of the waste; and geological disposal which entails isolating the waste in a geological medium (an ice sheet, sediment, or rock beneath the deep seabed or sediment or rock on land) in such a way that maintenance and administrative controls, as is the case with storage management facilities, would not be required in the long-term.

The nuclear reactors and waste storage facilities are also anthropogenic sources of emissions of ionizing radiation (radionuclides) and waste heat to the atmosphere.

The fossil fuel-fired thermoelectric power plants, generate large streams of wastewater which, in terms of toxic chemical content, are rather clean (Thors et al., 1998). Therefore, these are either recycled or discarded to a surface water body with minimal effect on the chemical quality. However, the impact of waste heat on ambient water temperature for plants where once-through cooling is practised, can be significant. An ambient temperature increase $> 2^{\circ}\text{C}$ can radically alter aquatic flora and fauna communities. Other less plentiful liquid effluents from fossil fuel fired plants can significantly affect water quality. Effluents from coal-fired steam include discharges from the cooling system and boiler blowdown, demineralizer backwash, a resin regenerator, and ash transport wastewaters, run-off from coal, ash piles on site as well as other miscellaneous low volume wastewater, and discharges from accidental leaks and/or spills. Trace metals such as Selenium (Se), Nickel (Ni), As, Cu, Pb, Zn, acids, and other chemicals are found in the effluents (Batley, 1996).

In addition, coal, oil, and gas fired power plants are known major anthropogenic sources of atmospheric pollutants such as sulphur dioxide (SO_2), particles (dust, smoke, and PM_{10}), nitrogen oxides (NO_x), toxic persistent organic micro pollutants (ToMPs), trace metals (Pb and Cd), greenhouse gases (carbon dioxide, CO_2 and methane, CH_4) ozone (O_3) formed from NO_x , and volatile organic compounds (VOCs) such as benzene.

Hydropower and the new and renewable energy sources: geothermal, solar, wind, and tidal, are rather clean sources of energy in terms of the generation of solid wastes, wastewater, effluents and gaseous emissions. A comparative overview of global emissions of greenhouse and sulphur gases from different energy sources by Ármannsson and Kristmannsdóttir (1992) is depicted in Table 1.

Geothermal development produces significant amounts of solid wastes and suitable disposal methods need to be found. Because of heavy metals, and particularly the semimetal arsenic, contained in geothermal water these solid wastes are often considered hazardous. While special hazardous waste disposal sites are present in the US and Europe, in many countries all over the world, these wastes need to be disposed of in the local area.

Peralta et al. (1998) studied environmental impacts of scale, sludge and drilling mud from three geothermal fields (Bulalo, Philippines, Cerro Prieto, Mexico, and Dixie Valley, USA) which have been

found to contain As, Cu, Cr, Zn, and Pb at levels above the earth's crustal abundance. Several techniques and procedures were used in the research work to assess the risks posed by the geothermal solid residues on disposal such as whole rock analysis, X-ray diffraction, radioactivity counting, protocol leach tests, toxicity testing, accelerated weathering test and acid mine drainage potential tests.

TABLE 1: Carbon dioxide and sulphur dioxide emissions from some power plant types
(Sources from Ármannsson, 1997)

Plant type	CO ₂ (g/kWh)	S (g/kWh)
Fossil fuel: Coal	1000	11
Oil	850	11
Gas	550	0.005
Geoth.: Steam	96	6
Hot dry rock	11	0
Solar: "SEGS" ¹⁾	140	0
Battery	0	0
Hydro power	0	0
Nuclear	<1	0

¹⁾ Solar Energy Generating Systems based on "Rankine cycle steam turbine system" which employs gas for top loading.

The results revealed no evidence of toxicity and genotoxicity to microorganisms, indicating that the existing genotoxicants and toxicants are bound to the silica matrix of the residues or are present in the form of insoluble sulphides and silicates as confirmed by XRD and leaching tests.

The radionuclides detected were Th-230, Pb-210, Ra-226, Ac-228, K-40 and total U. Ra-226 needs monitoring since it decays to radon, which is toxic when inhaled. All the activities fall within the range of naturally occurring materials (NORM) with the exception of Pb-210 ($t_{1/2} = 22$ years) in a sample of scale. The level of radioactivity, however, was within occupational dose limits.

Leaching tests gave negative results indicating that the wastes can be classified as non-hazardous. However, in a worst case scenario, using the finer particle size of $<125 \mu\text{m}$, 20% of Pb was found to be leached to concentrations above regulatory limits. Other elements such as Fe, Na, and Zn were also leached to some extent at different particle sizes. Some of the samples did not give positive results for acidification potential with any of the regulated elements (As, Cr, Cd, Ba and Pb) in the leachate after three months of weathering tests, implying that an even more aggressive environment would be necessary to eventually release the heavy metals.

However, in the research paper, a confirmative kinetic test for acid mine drainage potential and bioleaching was recommended. In addition, computer simulation of leaching using thermodynamic models to predict equilibrium reactions and concentrations is a requirement. Modelling results should be comparable with experimental data.

Geothermal energy, if properly implemented, is a sustainable resource and benign to the environment (Fridleifsson, 1997). Emission of greenhouse gases is minimal compared to fossil fuels. The removal of H₂S from high-temperature steam, reinjection of spent geothermal fluids into the ground, disposal of drilling mud, sludge, scales and other construction and maintenance debris in properly designed and managed landfills, and careful storage and handling of toxic and hazardous dosing chemicals and petroleum products make the potentially negative environmental effects negligible.

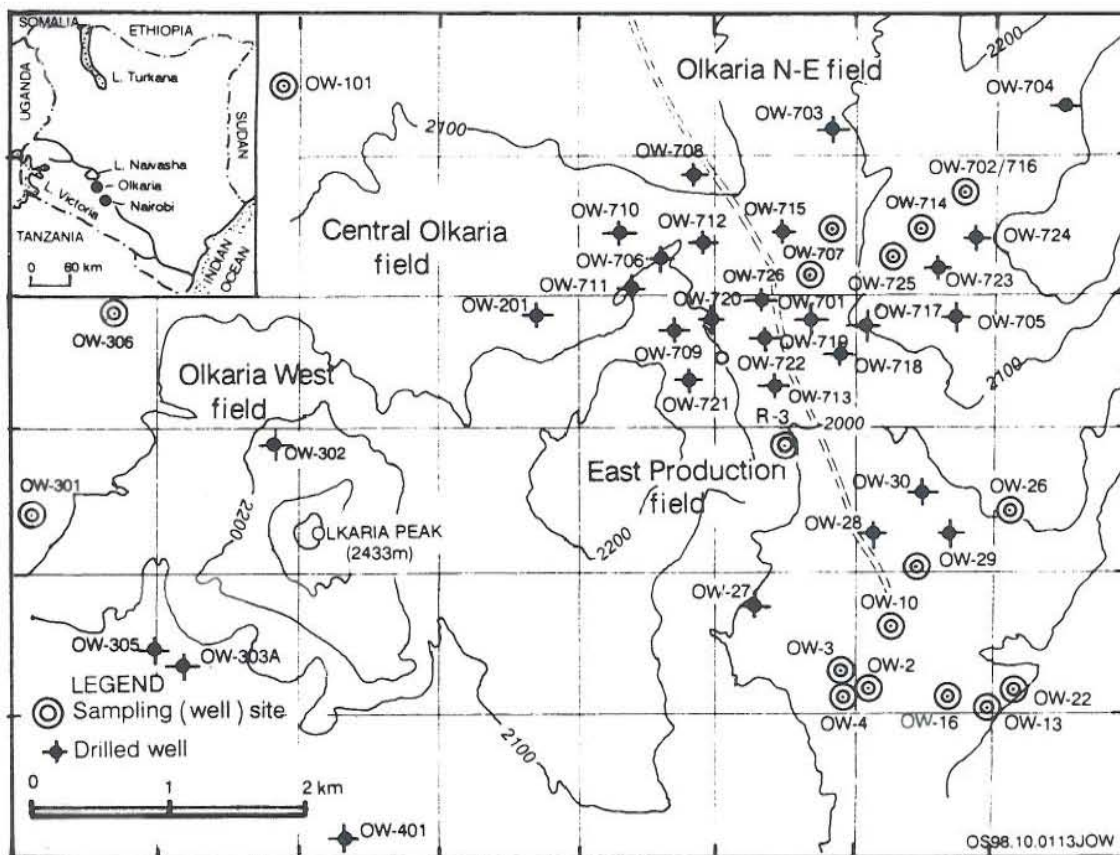


FIGURE 1: The Olkaria geothermal field and location of sites for monitoring of environmentally significant chemical elements

3. OVERVIEW OF OLKARIA GEOTHERMAL FIELD

3.1 Environmental conditions

The Olkaria geothermal field is situated in the eastern branch of the great African Rift Valley. It is located within Hell’s Gate National Park, approximately 125 km northwest of Nairobi, the capital city of Kenya (Figure 1). The management of the wildlife in the park is under the jurisdiction of the Kenya Wildlife Service (KWS) which has drawn up, jointly with the management of the Kenya Electricity Generating Company (KenGen) Limited, a memorandum of understanding stipulating environmental management criteria to minimize environmental contamination and associated risks. The document, though not legally binding, is signed by the management of the two major stakeholders in the geothermal development field.

The field is situated in a semi-arid area classified as eco-climatic zone 5, with long periods of little rainfall and low carrying capacity. In the vicinity of the field there are horticultural, cattle ranching, and residential premises for permanent and casual workers of the farms. Some employees of KenGen reside in camps and estates within and in the vicinity of the Olkaria geothermal field. In addition, a small population of the native Maasai community who are nomadic pastoralists, live in make-shift homesteads outside the park area. The southern section of the field is located close to one of the fresh water lakes in the rift valley, Lake Naivasha, which is the lifeline for all the developmental activities in the region (Figure 2).

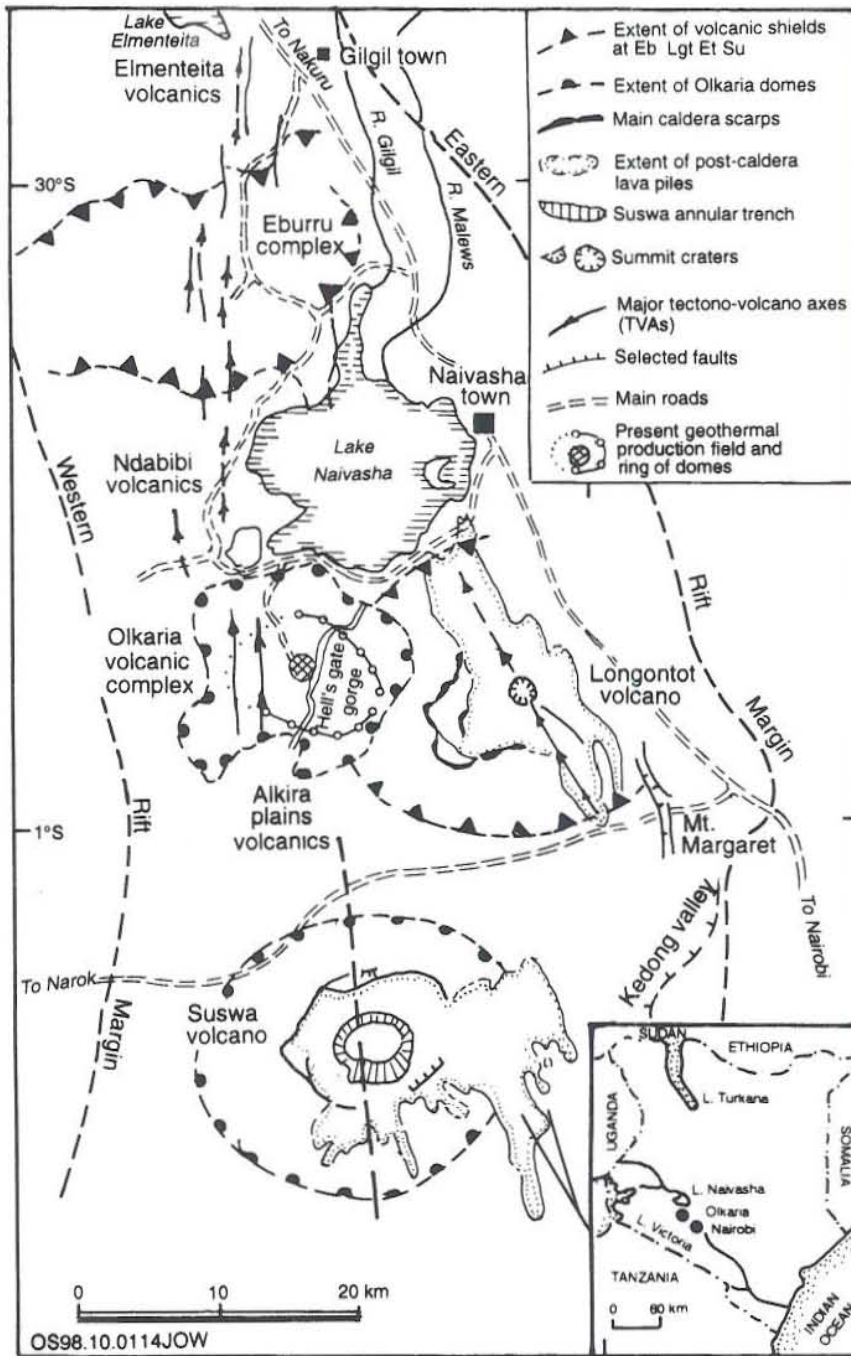


FIGURE 2: Location of Lake Naivasha and recent volcanic centres and features in its vicinity

The Olkaria geothermal project utilizes the lake water for drilling, make-up water for the cooling tower of the electric power plant, and for domestic consumption. More so, it is one of the Ramsar sites (wetlands of international significance), as it constitutes a resource of great economic, cultural, scientific, and recreational value, the loss of which is irreparable. The Government of the Republic of Kenya is one of the signatories of the Convention on Wetlands signed in Ramsar, Iran in 1971. The convention referred to is an intergovernmental treaty which provides the framework for national and international cooperation for the conservation and wise use of wetlands and their resources.

The stakeholders in Lake Naivasha, including Lake Naivasha Riparian Association (LNRA), KenGen, KWS, Naivasha Municipal Council and departments from various government ministries, have co-authored a management plan for the lake. Each stakeholder is represented on the management plan implementation committee.

One of the requirements of the management plan is the development of environmental codes of conduct for each sector. The main aim of the code is to promote wise use and conservation of the lake and its resources. KenGen for its part, has drafted a detailed environmental code of conduct for the geothermal energy sector which incorporates the independent power producers expected to develop the western sector of Olkaria geothermal field.

The above mentioned agricultural activities, human, and wildlife habitations, however, have co-existed with geothermal exploitation in the area since 1970 when exploration commenced.

3.2 Status of geothermal development

The Olkaria field reservoir is two-phase with sub-surface fluid temperatures above 200°C. The field is divided into four sectors: East, Northeast, Central and West Olkaria fields for management purposes.

In Olkaria East field, there is a 45 MWe geothermal power plant, fully commissioned in 1985. Thirty three wells have been drilled in this field, seven of which are make-up wells for steam decline for wells that have been producing since 1981. Thirty wells in total, have been drilled in Olkaria Northeast field and discharge tests have proven a steam equivalent of 74 MWe. Bidding for construction of a 2 x 32 MWe is already underway. The Olkaria West and Central sectors and other fields in the vicinity of Olkaria geothermal field: Domes, Longonot, Eburru, and Suswa, are still under exploration (see Figure 2).

3.3 Statement of environmental challenges and mitigation options

The large volume of waste geothermal fluids generated during the energy production process is of major environmental concern. Merz and McLellan - Virkir (1977) estimated a 120 m³/h flow rate of geothermal waste fluid from the 45 MWe power station. Moreover, the volume of the geothermal waste fluid output, is envisaged to increase, both in Olkaria when the planned 64 MWe in the Northeast Olkaria field is installed, and more so when other sites around the country are harnessed.

Each well in the field under production is equipped with a well head separator and stabilizing pond systems for wastewater and solid residue settlement. Most of the separated wastewater drains through open concrete channels into one main evaporation or infiltration lagoon for containment before re-injection.

Chemical analytical results for the wastewater and power plant effluents show that they contain high concentrations of dissolved chemical components and trace elements of environmental significance, most of which are below maximum tolerable levels, with the exception of fluoride whose concentration is particularly high in the Kenyan rift waters (Tole, 1990). Levels of trace elements and other chemical components depend on the physiochemical properties of the hydrothermal reservoir. However, it is clear that direct release of the wastewater to the surface environments, in the process of geothermal resource exploitation, could be a source of environmental contamination.

Contamination of soil, vegetation, and surface water components of the environment in Olkaria field are of immediate concern. Trace elements such as mercury and arsenic are capable of bioaccumulation higher up in the food chain with eventual toxic effects on the biosphere.

In the operating Olkaria East field, a strategy of re-injection is planned both as a disposal mechanism for the wastewater and for managing the decline in steam production and falling reservoir pressures. Injection and tracer test experiments, resultant data analysis, and interpretation for thermal efficiency of re-injection have shown that it is feasible and that injection of hot water ($T > 100^{\circ}\text{C}$) at the rate $< 50 \text{ m}^3/\text{h}$ would be preferable (Ofwona, 1996) for the dipole around wells OW-03 and OW-04. The implication of injection results, coupled with the low rates, is that some wastewater would still be left in the surface environment.

Monitoring on a quarterly basis of the concentration levels of ten environmentally significant chemical elements: Zn, Cu, Pb, Li, Cd, Ba, F, B, As and Hg in well discharge, separation plant discharge, power plant blow-down condensates, potable water, soil, and vegetation within and in the vicinity of Olkaria geothermal field, has been in progress since 1993. This has been adopted as one of the pollution control criteria and the details are described in Chapter 6 of this report.

4. CHARACTERIZATION OF GEOTHERMAL AND ASSOCIATED WASTE MATERIALS

Waste characterization and classification is an emerging tool in environmental engineering utilized in the identification of the true nature of waste prior to and after disposal. It is quite often applicable as a first step screening procedure during environmental impact studies of waste materials. In this case, the environmentally significant geothermal and associated waste properties: material type, origin, chemical content, and environmental behaviour of the potent chemical contaminants, are considered. More so, an attempt is made to quantify the identified categories which is a necessary prerequisite in planning for environmentally acceptable waste treatment, storage and disposal.

4.1 Solid wastes

Geothermal developmental processes produce significant amounts of solid wastes which include drilling mud, sludge, scales, and other construction and maintenance debris.

In the process of geothermal drilling, large quantities of solid wastes are produced in the form of the drilling muds, petroleum products from lubricants and fuels, and cement wastes. Drilling muds consist of a number of mud chemicals: viscosifiers (sodium bentonite, polymers, CMC), filtrate reducers (polymers), thinners and dispersants (lignite, lignosulphates, water), friction reducers (potassium sterate), foamers, surfactants (detergents-soap), loss of circulation materials (wood shavings, seed hulls), and water chemistry adjusting chemicals (sodium hydroxide, sodium carbonate). In addition to bentonite, other chemicals such as perlite, silica flour and retardants are mixed up with cement and utilized during well cementing processes.

Drilling muds are either lost to the circulation in the well or end up in the drilling sumps as solid waste for disposal. The muds are produced, after drilling, as solid alkaline wastes that may contain large concentrations of chromium (Cr), together with many other chemicals (Peralta et al., 1996), as shown for the Mexican drilling mud (MDM) in Table 2.

Sludge is a precipitate of dissolved minerals that forms during cooling of the separated hot brine at the sludge sump of cooling towers of geothermal power plants or holding ponds prior to disposal. Whether there is H₂S abatement or not, these are normally predominantly sulphur with the possibility of Hg contamination. If a Stretford process has been used for H₂S abatement, then there is the possibility of vanadium (V) contamination, as well as contamination from a number of other trace elements (see Table 2).

Scale is deposited in steam gathering systems, well bores, separators and turbine blades and is removed during preventive maintenance shut-down. Composition of trace elements in some geothermal scales is shown in Table 2.

TABLE 2: Trace elemental composition of some geothermal residues in ppm
(modified from Peralta et al., 1996)

Type	Co	Ni	Cu	Zn	As	Sb	Cd	Ba	Hg	Pb
Philippine scale	4	68	188	112	256	53	<1	139	0.041	165
Philippine sludge	12	17	183	302	302	98	<1	636	0.241	102
American scale	<1	9	144	24.4	<3	30	<1	908	0.266	23
Mexican drilling mud	3	8	42.1	57.8	11	<5	<1	682	0.023	47
Mexican sludge	1	<1	9080	15900	<3	1190	2	92	0.005	11600
Mexican scale	<1	<1	23.9	26	-	31	<1	14	0.015	11
Kenyan sludge	-	-	1.6	0.467	0.017	-	<1	0.167	0.001	0.6

The other principal solid waste is construction and normal maintenance debris. The latter is considered hazardous due to the presence of asbestos in insulation material. Demobilization of geothermal exploration and utilization facilities are also associated with abandoned power plants, equipment and scrap.

4.2 Liquid effluents and wastewater

During drilling, cuttings from the drill head are flushed out with water often mixed with drilling detergents to assist in the collection of rock formation cuttings.

Typical chemical composition of bentonite and perlite according to analysis reported by Ármannsson (1997) and for samples of geothermal residues from Philippines, America, and Mexico geothermal fields studied by Peralta et al., (1996) is as indicated in Table 3. The results show that most of the geothermal residues consist mainly of silica in the range of 60-80% by weight.

TABLE 3: Chemical composition of samples of geothermal residues in % by weight (modified from Ármannsson, 1997; and Peralta et al., 1986)

Material	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	TiO ₂	CaO	MgO	Na ₂ O	K ₂ O	LOI ¹	Water solubility	Acid solubility
Philippine scale	75	3.22	10.3	0.277	0.82	0.35	0.59	0.74	-	-	-
Philipp. sludge	66	9.3	6.92	0.481	2.18	1.07	1.52	1	-	-	-
American scale	67.3	10.4	0.22	<0.001	2.97	0.32	1.85	2.54	-	-	-
Mex. drill. mud	68.7	7.39	2.4	0.342	6.55	1.43	1.98	1.64	-	-	-
Mexican sludge	74.8	4.94	5.57	0.002	0.47	0.03	1.78	1.73	-	-	-
Mexican scale	82.1	0.05	0.14	<0.001	0.62	0.02	6.78	1.81	-	-	-
Bentonite	64.1	20.0	3.66	0.16	1.52	2.38	2.18	0.49	6.26	0.1	0.5
Perlite	73.0	12.5	0.7	0.1	1.0	0.5	4.5	4.8	1.3	0.1	0.5

¹ Loss on ignition

The detergents used, such as bentonite drilling mud mixed with some barium material, are those capable of withstanding high temperature. If the well erupts, a heavy substance such as barium sulphate (BaSO₄) is usually added. These chemical components constitute the effluents from drilling operations. However, these are inert materials similar to a hard compacted surface.

After completion tests, wells are normally closed to warm up and build up pressures common for artesian wells. However, for non-artesian wells, it is common practice to compress them using compressors and leave them shut-in for a while to build up pressure. During compression time, drilling soap is normally added. As a result of subsequent well testing, hot waste steam and liquid carry-over or spray containing soap but mainly SiO₂ and other volatile elements such as B, Hg, are emitted. This effect is most severe during vertical discharge effected to clean up wells. In addition, large volumes of wastewater are produced from wells under test, the composition of which depends on the chemistry of the hydrothermal system.

However, the principal liquid effluents are the separated wastewater from separator facilities and blowdown from condensers. The chemical composition of the effluents depends largely on the geochemistry of the reservoir and the operating conditions utilized for power generation. Reservoir chemistry will be different for different fields. For example, geothermal well fluids of the Northeast Olkaria geothermal field in Kenya, are near neutral and relatively dilute (pH 6.7-7.4, Cl 350-500 ppm (Wambugu, 1996) whereas those of the Salton Sea geothermal field in the USA, hosted by evaporite

deposits, are acid and highly saline ($\text{pH} < 5$, $\text{Cl} > 155,000$ ppm (Brown, 1995)). However, most geothermal effluent waters contain high concentrations of SiO_2 and at least one of the following contaminants: B, As, H_2S , Hg, and sometimes NH_3 and other trace elements as shown in Table 4.

TABLE 4: Contaminant concentrations (ppm) in some selected geothermal fluids and gases, and in a world average fresh water (modified from Brown, 1995)

	Zn	Pb	Li	As	Hg	F	B	H_2S	NH_3
Freshwater	5.0	0.5	0.003	0.002	0.0004		0.01	<dl	0.04
Deep well waters									
Wairakei (NZ)	2.0	4.0	14	4.7	0.0002		30	1.7	0.2
Olkaria (Kenya)	11.9	3.66	-	<0.008	0.001	62.4	3.2	-	-
Steam (s) or non-condensable gases									
Wairakei (s)			-	-	0.002		0.23	52	4
Wairakei (nsg)			-	-	-		0.052	400	7.5

Steam condensates, on the other hand, have relatively high concentrations of H_2S , Hg, NH_3 , and to a lesser extent Radon (Rn), B and As. Consequently, these contaminants can become concentrated in the cooling water discharge (see Table 4).

4.3 Thermal emissions

The efficiency of geothermal power plants is much lower than that of other types of power plants. The conversion efficiency of conventional geothermal electric plants is about 5-20%. However, higher conversion efficiency of about 50-70% is attained through direct utilization of geothermal energy. Direct utilization has many technological, reliability, and economical advantages including environmental acceptability which have been demonstrated throughout the world (Fridleifsson and Freeston, 1993). Therefore, waste heat per MWe generated in geothermal power generating plants, is much larger than in other types of plants by a factor of about 9 and is approximately 80-95% and 30-50% of exploitable heat resources in cases of indirect and direct utilization, respectively.

4.4 Gaseous emissions

Geothermal power generation using a standard steam cycle plant results in the release of waste non-condensable gases, and fine solid particles into the atmosphere as shown in Figure 3.

In vapour-dominated fields and those in which all waste fluids are re-injected, gas in steam is the important discharge from an environmental perspective (Webster and Timperly, 1995). The most significant continuous gas emissions are from gas ejectors of the power plant, but discharge often occurs during well drilling, bleeding, clean-outs and testing as well as from line valves and waste bore water degassing, usually insignificant in comparison.

Although carbon dioxide (CO_2) is close to 90% by weight (Bogarín, 1996), the geothermal gases can include very high concentrations of hydrogen sulphide (H_2S) gas. Geothermal waste gases may also contain ammonia (NH_3), trace amounts of Hg, B vapour, hydrocarbons such as methane (CH_4) and ethane (C_2H_6), arsenic, and radon.

The rig auxiliaries such as generators and compressors also produce gaseous wastes of non-condensable gas emissions and exhaust smoke.

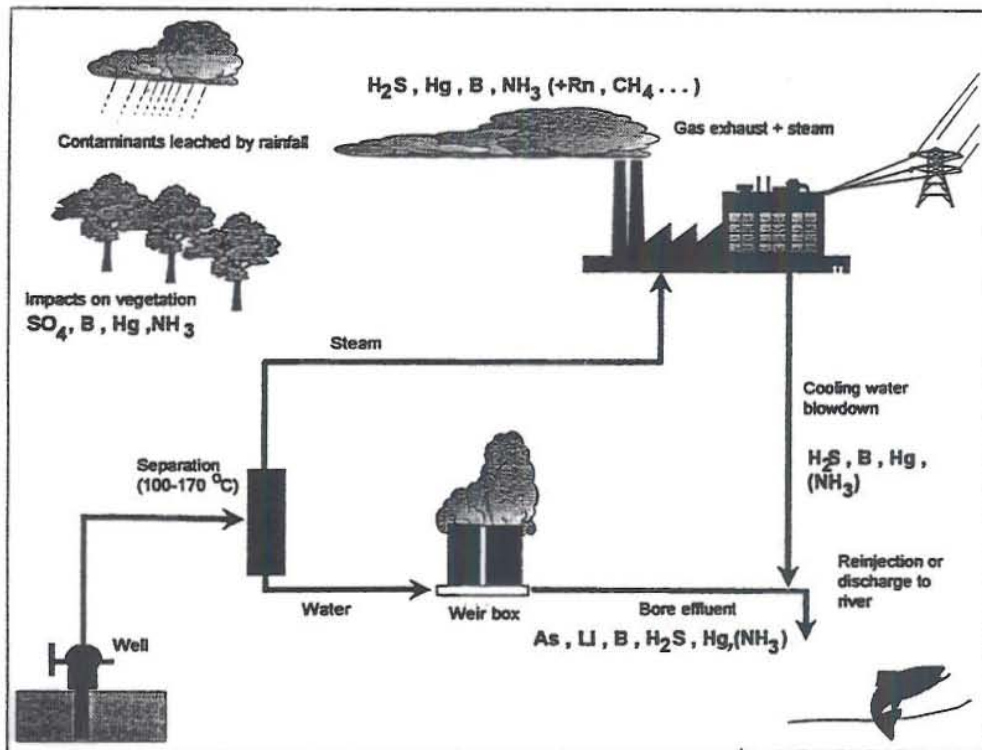


FIGURE 3: A summary of the discharges and main chemical contaminants from a steam-cycle geothermal power plant on a hot-water geothermal field

4.5 Toxic substances and hazardous wastes

Hazardous wastes produced during drilling include petroleum products from lubricants and fuels and cement spills. Over a typical drilling period for a single well, about 300,000 and 3,000 litres of fuel and lubricants, respectively, are used. Cement waste products from well cementing jobs are not normally considered hazardous, although some additive constituents such as silica flour may be hazardous on their own. Where H₂S abatement is required during drilling in vapour dominated systems or in electric power generation process, chemicals for treatment and abatement such as copper sulphate, NaOH, vanadium or iron oxidation agents, citric acid, Fe₂O₃ catalyst, H₂O₂, and BIOX reactant, may be considered hazardous.

Other potential sources of contamination are hazardous liquid chemical spills or leaks from motor vehicles, rig, and power plant maintenance and operations which are unpredictable, but usually avoidable. The latter is often due to operational mechanical failure and/or human error. The common chemical products of concern are fuels, lubricants, biocides and other dosing or specialist chemicals such as transformer fluids. Maintenance debris is also considered hazardous due to the presence of asbestos in insulation material.

4.6 Sanitary waste

Sanitary wastes are often associated with any developmental process and geothermal energy exploitation is no exception. Though of less significance in terms of quantity, this category of wastes needs to be accorded due consideration. These include service wastes consisting of materials such as paper and plastics from the offices and unusable inert and hazardous items from storage facilities; household wastes such as organics, paper, textile, rubber, metals, wood, and glass from staff estates and camping sites; and clinical wastes such as expired drugs and infectious materials from health clinics, located and operated within or in the vicinity of exploited geothermal fields as is the case with Olkaria field, Kenya. This category also includes sanitary wastewater and sludge from residential houses located within or in the vicinity of many geothermal fields under exploitation.

5. CONCEPTS OF WASTE MANAGEMENT AND POLLUTION CONTROL

5.1 Environmental legislation on waste management and pollution control in Kenya

Legal instruments to facilitate implementation of environmental management policy have been lacking in Kenya. Therefore, environmental control of geothermal development within Kenya has been subject to the requirements of both specific legislative acts that relate to different aspects of the environment, the common law, and the World Bank operational directives on the EIA process.

Some of the Kenyan legislative environmental pollution control acts relevant to geothermal development are the Public Health Act, the Wildlife (Management and Conservation) Act, the Waters Act and the Factories Act as well as many other statutory regulations. The four acts contain directives regarding regulation of activities that may affect wildlife, domestic animals, human health, and safety. There exist provisions within these acts to deal, in a general way, with surface and ground water, air and noise quality. Emissions such as wastewater and gases which could be regarded as injurious to health are defined as environmental nuisances and emitters are liable to prosecution.

However, a bill on environmental management including EIA and reporting has been drafted by the National Environmental Secretariat of the Ministry of Environmental Conservation. The draft bill is currently with the parliament awaiting debate, approval and implementation. The minister in charge of implementation of the environmental law, will be vested with powers to prosecute owners of premises responsible for wastes and emissions detrimental to the environment and human health.

Industries, including geothermal premises, would be required to practise environmentally acceptable waste management and pollution control criteria that may include adoption of cleaner best available techniques not entailing excessive costs.

5.2 General principles and benefits of pollution control and waste management

One of the common principles utilized in waste management is the hierarchy of waste management options, viz: minimization of waste amount, reuse of discarded materials, recovery of waste by all means possible, and at last, safe final disposal of all waste which cannot be treated by the methods mentioned.

Benefits of integrated pollution control and waste management are both environmental and economical. Often, companies which wholly embrace pollution monitoring strategies get in control and can effectively formulate management, containment, and minimization of releases to all the three environmental media. The benefit is therefore, reduced environmental pollution, and a minimization of impacts on the environment as a whole.

Long term economic benefits are the result of the reduction in the use of inputs such as water, energy, and raw materials. Environmental economic analysis has shown that pay-back is possible at three levels, i.e. first order savings related to good housekeeping, second order savings resulting from the analysis of product losses and de-bottlenecking, and third order savings due to changes in ethos from end-of-pipe techniques to inherently clean processes. It is, therefore, a notable fact that pollution prevention pays a great deal.

5.3 Geothermal waste management criteria

Management of geothermal waste emissions to minimize environmental pollution can be achieved through the prevention or minimization of waste, recycling and reuse, incineration, landfills, sump, stabilizing and infiltration pond systems, re-injection, and careful handling of wastes depending on their specific nature.

5.3.1 Solid waste management

Disposal of hazardous solid wastes on site is a vexing problem in cases where large volumes are generated. However, most of the solid geothermal wastes from exploration and utilization processes are non-hazardous and in low quantities with the exception of scale residues and, therefore, pose fewer management problems.

The geothermal residues contain trace amounts of toxic chemical elements such as Co, Ni, Cu, Zn, As, Sb, Cd, Ba, Hg, Pb which are regulated by international and national directives/regulations and environmental protection laws. Therefore, disposal into surface environments is unacceptable and should be avoided.

The temporary containment drilling sumps used for drilling effluents and mud, need to be lined with impervious materials to prevent leaching of the contaminants capable of infiltrating into the soil media.

If possible, it is advantageous to dispose of drilling muds, sludge and scale in the form of slurry into deep reinjection wells cased to protect the meteoric aquifers. If this is not possible, then total containment with no significant emissions to air, surface water or groundwater, as in landfill disposal systems, should be employed. In the later, leachate confinement, monitoring, and computer simulation using thermodynamic models to predict equilibrium reactions and concentrations are necessary requirements. The simulation results must be comparable to monitoring data. Care must also be exercised in the handling and transport of solid geothermal residues to prevent physical contact and spills. Use of proper protective gear by personnel is highly recommended.

The situation regarding silica scales, though of little commercial value, might change if recent research in Iceland, Mexico, and New Zealand leads to a commercial process for refining the silica into a saleable product (Fridleifsson and Freeston, 1993). There is a variety of markets and possible uses for amorphous silica which, depending on the form and purity, can be worth up to 15 US\$/kg.

The solid waste disposal sites that may include prohibited primitive open dumps, need periodic monitoring. Geothermal operators need to be aware, early on, of the possibility of such sites becoming long term liabilities in terms of pollution clean up costs.

During demobilization after a drilling operation, a slotted liner is put in, the drill rig is transported away and flow equipment: pipes, additional gas vents, and atmospheric separators or silencers are erected. Quite often, some equipment and scrap metals are abandoned in the process. In the worst case scenario, the power plant facilities may also be abandoned after a shutdown. Under such situations, an inventory of the type and operational status of the equipment must be carried out. Thereafter, the feasibility of recovery, recycling and reuse of equipment and scrap is evaluated and effected as appropriate. This is followed up by the execution of a planned, careful, and organized removal of the physical facilities. The sites must then be cleared and rehabilitated to acceptable standards.

Normal construction debris is classified as non-hazardous. However, this is generated in large quantities, hence the need for proper management. The preliminary step would be to carry out a sorting of wastes into different categories in terms of material types such as timber, concrete, metals, paper, plastics etc., then identify the materials that can be recycled and reused and finally dispose of the unusable wastes through incineration and landfill.

5.3.2 Liquid effluents and wastewater management

A geothermal resource is exploited by drilling wells to depths ranging from a few hundred metres to the maximum economic depth of about 3000 m. The fluid at the wellhead is either steam, water, or a mixture of water and steam depending on the nature of the reservoir. Two-phase bore fluid has to be separated into steam and water fractions. In early power plants separation was effected at the wellhead

and the two phases transmitted in separate pipelines or channels, the steam to the power station and the separated water either flashed to the atmosphere or carried to the waste disposal option in open channels. Examples of such installations are Olkaria, Ahuachapan (El Salvador), Cerro Prieto (Mexico), and Wairakei (New Zealand). In recent plants, a number of wells are grouped together with pipelines carrying two-phase fluid. Separator stations sited in the steam field and close to the planned power plant are then used with pipelines transmitting steam to the station and wastewater to injection wells.

In the first case scenario, the wastewater and its chemical and thermal load, should be managed through a system of concrete-lined stabilizing ponds and drainage channels, and infiltration ponds prior to reinjection. A considerable ongoing maintenance programme is also needed to keep the surface drainage system free of silica which deposits in the channels upon cooling,

Geothermal condensers often employ direct contact spray type systems. These have the advantage of offering lower capital costs for a system that does not require the condensate to be pure for recycling to a boiler. A part of the non-condensable gases, mainly NH_3 and H_2S , dissolves in the condensate/cooling water mix introducing a contaminated stream of highly corrosive water. Therefore, the disposal channels for the condensates must be concrete-lined or gravelled to prevent infiltration of the concentrated contaminants into sediments.

Apart from the chemicals, the significant heat content of the wastewater can be put into other uses as described in Figure 4 (Fridleifsson and Freeston, 1993), thereby improving the thermodynamic efficiency of geothermal plants. This is an environmentally acceptable manner of managing waste thermal emissions by considerable reduction of temperature.

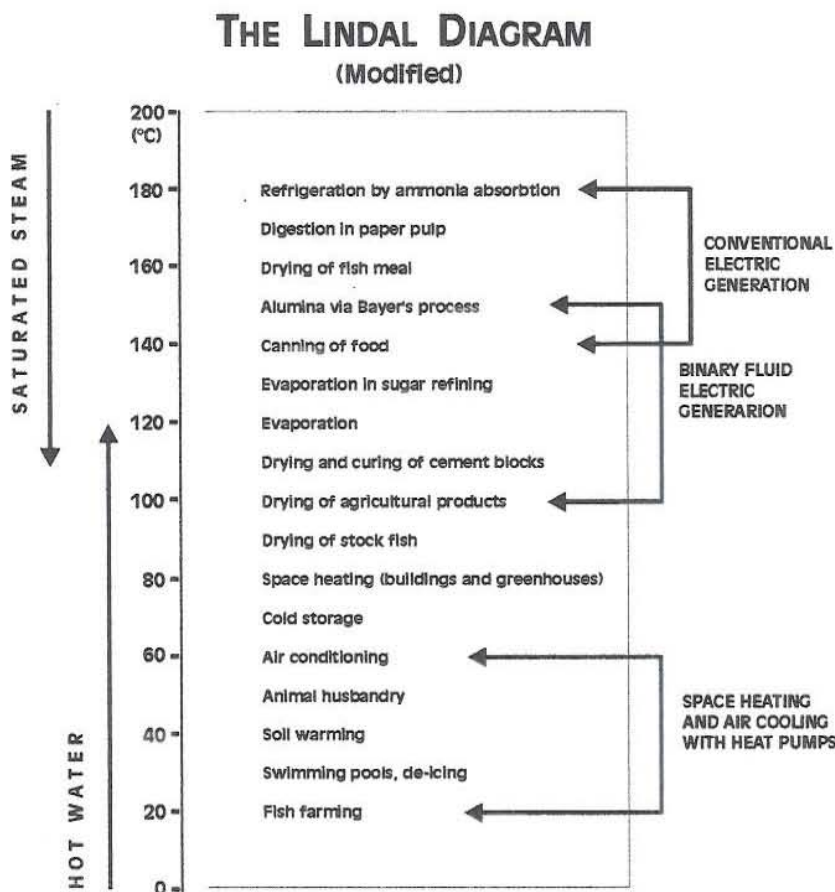


FIGURE 4: The LINDAL diagram on typical fluid temperatures for direct applications of geothermal resources (Fridleifsson and Freeston, 1993)

Nevertheless, both the chemical and thermal impacts can be avoided by reinjecting the separated wastewater and condensate into the reservoir. However, re-injection of the acid condensate water from the cooling tower has to be in separate wells which are specially designed with casings to handle corrosive fluids.

The drilling effluents and mud are best managed through temporary containment sump pond systems to avoid uncontrolled flows and, if possible, reinjected immediately into deep wells cased from meteoric aquifers. The landfill disposal option for the remnant solid alkaline residues should be utilized.

Similar management options are appropriate for contaminants and thermal emissions from wells under test after completion. However, silencer-separator facilities employed

must be upgraded to enhance their separation capacity and efficiency. Use of the cyclone type of separators is recommended for wells with notably large outputs.

There are other wastewater and effluent management options of interest for power stations that are still under research. These include conventional chemical treatment involving precipitation and sludge settling and biological (anaerobic) reactors and wetland (two-stage) systems for recovery and reuse of chemical contaminants (Batley, 1996). However, the concentration of the trace elements is so low in absolute terms that the conventional chemical treatment is prohibitively costly given the large volumes of wastewater involved.

A potentially cost effective alternative to chemical treatment is provided by systems that make use of natural biological processes. Indeed, biological removal processes tend to work best for low concentrations of trace elements. One possible biological option is a constructed wetland consisting of one or more shallow pits containing plants and algae. Mechanisms in wetlands that immobilise trace elements include precipitation (as insoluble sulphides), filtration, adsorption, microbiological transformation (often mediated by sulphate reducing bacteria) and plant uptake. A possible alternative biologically based treatment system uses purpose-built reactors where microbiological processes are used to remove trace elements from solution. These systems have the advantage of requiring much less land area than the wetlands. However, further research is still required to develop the above technology to the stage where it can be applied at the pilot field stage.

5.3.3 Abatement of gaseous emissions

In natural geothermal features, the impact of the geothermal chemical contaminants may be controlled by deposition close to the features or fixation in soils and sediments. Hg and As, for instance, can be precipitated in silica sinters and NH₃ can readily be taken up by soils.

Of the waste non-condensable gaseous emissions, H₂S gas is of major environmental concern during geothermal drilling and power generation operations. However, a number of common abatement or removal processes are available. The details of some of the best available cost effective methods have been reviewed by Bogarín (1996). The redox process is recommended as a first stage process to reduce H₂S to about 99.9%, followed by activated carbon filtration in a packed tower or a scrubbing tower with a solution of potassium permanganate. These processes have wide application in industry, however, the main problem is disposal of waste sub-products such as elemental sulphur, especially if they contain traces of vanadium. Re-injection of non-condensable gases along with separated wastewater solves disposal problems and has been reported for the Coso field (U.S.A.).

5.3.4 Toxic substances and hazardous waste management

During the operation of power stations, there is need for special safe storage provisions for hazardous materials such as lubricants and fuels, chemicals for cooling water treatment including biocides, chemicals for abatement processes and specialist chemicals for transformer fluid as well as other dosing chemicals. Likewise, fuels, lubricants, mud chemicals such as silica flour and H₂S gas abatement chemicals used during drilling must be treated in the same manner.

Adherence to the control requirements of the regulations for safety and environmentally sound practise detailing storage and transport of petroleum products and other hazardous chemical products, which vary from one country to another, is imperative.

Cases of accidental oil spillage must be avoided to the extent that is mechanically and humanely possible. Occasional unpredictable spills must be addressed with due care to minimize pollution of soil and destruction of vegetation. Some oil spill prevention measures using mechanical oil traps are recommended. The waste oil products generated from the power station, motor vehicle and rig

maintenance workshops can effectively be managed by use of storage tanks prior to recycling to either the oil companies or those utilising waste oil in other manufacturing processes. Basements of the pits of workshops should be lined with concrete to avoid contamination of soil by waste oil and grease spills.

Disposal of some hazardous maintenance debris containing asbestos needs to be close to the area of production. This will minimize transportation of the debris over large distances which can allow escape of fibres into the atmosphere enhancing the risks of inhaling the asbestos fibres. Dumping in pits about 2 m deep and rehabilitating the site by covering it with soil followed by revegetation is adequate (Dr. Lúdvík E. Gústafsson, Environmental and Food Agency of Iceland pers. com.).

Some hazardous clinical wastes can be managed through a pathway composed of five elements, each of which must be addressed in terms of personnel and material costs, and occupational and safety risks. The five management elements include separation, identification, handling (measurement, storage, transport), treatment and disposal provisions (Eugene, 1998).

5.3.5 Sanitary waste management

Sanitary wastes can be divided into two categories: household solid wastes and wastewater, and sludge for management purposes. The quantity of sanitary wastes generated is rather small because geothermal development is highly specialised and not labour intensive. Management of wastewater by use of conventional septic tank systems is adequate. However, the tanks must be emptied regularly by the council authorities in charge for further treatment and disposal.

The household solid wastes on the other hand, can effectively be managed by employing conventional municipal solid waste management criteria involving household collection, sorting, recycling and reuse, incineration, and safe disposal in landfills.

6. POLLUTION CONTROL - MONITORING OF ENVIRONMENTALLY SIGNIFICANT CHEMICAL COMPONENTS AND TRACE ELEMENTS IN OLKARIA GEOTHERMAL FIELD, KENYA

6.1 Background information

Environmentally significant elements such as Zn, Cd, Pb, Cu, Li, Ba, As, Hg, F, and B occur naturally in the earth's crust. These elements are released to the environment under natural weathering conditions and by volcanic eruptions. Other principal sources for the atmosphere are wind-borne soil particles, sea salt sprays and wild forest fires. However, trace element cycles in the environment have been profoundly modified by anthropogenic activities such as burning coal and oil, and the processing of ores. The biogenic sources account for an average of about 30-50% (Nriagu, 1989) of global baseline emissions, implying that mankind has become the most important agent in the global atmospheric cycling of trace elements.

Modern industrialisation, coupled with increased energy demand, has led to greater releases of toxic trace elements to aquatic and terrestrial ecosystems. Domestic and industrial wastewater, effluents, and the dumping of sewage and sludge are some of the known sources of trace element pollution in aquatic ecosystems. Part of the pollutants often finds their way into terrestrial ecosystems such as soil and vegetation. Since each type of soil has a limited retention capacity for trace elements, there is a growing concern that many soils may become overloaded with toxic metals, given the current rate of anthropogenic input (Pacyna, 1988).

Exploitation of geothermal energy resource can be a source of trace element contamination of the environment (Ellis, 1975). The exploited geothermal fluids are usually associated with areas of recent

volcanicity where magma or hot intrusive igneous rocks are close to the surface and can heat up the percolating surface or ground water. The high temperature and pressure of the fluids and long contact periods with the rocks, increase the dissolution rate of components and elements constituting the rocks through which they pass. The dissolution reactions of the rocks also depend to a larger extent on their nature. Thus, the geothermal fluids acquire a chemical composition very different from the surface and/or normal underground waters.

The chemical composition of geothermal fluids is site specific and varies from place to place depending on the geochemistry of the underlying rocks and the hydrothermal condition of the reservoir. Typical geothermal fluids, however, contain trace elements such as Zn, Cd, Pb, Cu, Ba, As, Hg, and B dissolved in varying trace amounts or concentrations (Ritchie, 1961; Nakahara, 1978; Skinner et. al., 1967). Other chemical components such as NaCl, SiO₂, Li, and F occur in abundance.

To maximise exploitation of the geothermal resource at depths, wells are drilled down to 1-3 km depth. The consequence of this process is an increase in the volume of geothermal fluid discharges over and above that which would be obtained for normal surface discharges. Therefore, substantial amounts of the aforementioned components and trace elements are brought to the surface environment with a potential for causing environmental impacts due to contamination of surface or underground water bodies, soils and vegetation.

Most of the chemical components and elements are toxic to flora, fauna and humans depending on their bioavailability and concentration levels. Moreover, their impacts are aggravated further by the capability of undergoing bioaccumulation along the food chains, enhancing their potential to reach highly toxic levels of concentration. Therefore, these elements pose an environmental challenge to the development of geothermal energy.

Kenya has a great potential for developing geothermal energy. Geo-scientific data have revealed that Olkaria alone has heat flow equivalent to approximately 400 MWe (Clarke et al., 1990). A 45 MWe power plant in the Olkaria East production field has operated successfully since 1981 and bidding is underway for the construction of a second power plant in Olkaria Northeast field with a production capacity of 64 MWe.

The current electric power generating capacity in Kenya is 894 MWe. Of these, hydropower, thermal, geothermal, and Independent Power Producers (IPPs) contribute 584, 177, 45, and 88 MWe, respectively. The current national energy peak demand is 670 MWe, of which geothermal energy still contributes a base load power of 45 MWe and the remaining 525 MWe are contributed by hydropower and thermal plants. The national energy demand is estimated to be about 1,123 MWe by the year 2006 and to meet the demand new investments in power production by the Government of Kenya would be: Hydro 15%, thermal 35% and geothermal 50%. This was due to the realisation that geothermal energy can provide reliable power, as it is less dependent on meteorological factors than hydropower plants. Moreover, the cost of constructing a new geothermal power plant is extremely low compared to that of a hydropower plant, the high cost of exploration and the slow development process of geothermal energy worldwide, notwithstanding. Geothermal power is, therefore, considered a very important form of Kenya's indigenous energy and may contribute a much greater proportion of the country's electric energy demand in future.

6.2 Aims of the monitoring programme in Olkaria region

The monitoring programme for environmentally significant trace chemical elements in Olkaria field, has been in progress since 1993. This followed a recommendation made by the board of consultants of the then KPC Ltd. on the basis that trace elements, upon accumulation higher up in the food chain, pose enhanced toxic risks to animals and humans. Moreover, the Olkaria geothermal field is situated within a national park and is surrounded by horticultural, ranching, and residential premises.

Each of the chemical elements monitored: Zn, Cd, Pb, Cu, Li, Ba, As, Hg, F, and B has specific significant biological impacts on flora, fauna and human health depending on their bioavailability and concentration levels.

The aims of the monitoring programme are to determine the levels of concentration of the chemical components and trace elements in geothermal waste water, potable raw and treated water, steam condensates and effluents from the operating power plant, soil and sludge, and plant materials within and in the vicinity of the Olkaria geothermal field. Concentration levels determined are compared with set national and international standards and quality criteria. An assessment of the environmental contamination level is made based on these results. Evaluations as to whether exploitation of the geothermal resource could be a potential source of significant chemical contamination is attempted.

In the programme, total recoverable elemental concentrations are determined and not those of specific compounds of the respective elements. The elemental levels of concentration for the fields under exploration such as Domes, Eburru and Suswa, are to be adopted as baseline data for future reference when fields are exploited.

6.3 Review of case studies

Monitoring of trace elements of environmental significance has been done in other geothermal fields all over the world. One such notable geothermal field is Wairakei, New Zealand. Studies done by El-Hinnawi and Biswas (1981) on R. Waikato, New Zealand into which geothermal fluids are discharged from the Wairakei power plants indicated high levels of trace element contamination of water and vegetation growing along the river. In previous studies, Reay (1972) had also found high levels of arsenic in vegetation growing in the same river. Likewise, Weisberge and Zobel (1973) indicated that mercury levels rose to 1.0 mg/kg in the bottom sediments of R. Waikato following discharges from the power plants. In the same studies, fish in the river also showed an accumulation of mercury to levels ranging up to 0.8 mg/kg, above the accepted values of 0.5 mg/kg for human consumption.

Other related studies have shown that incorporation of heavy metals into flora is mainly achieved through uptake by roots from soils or water in which the plants are growing. So the levels and availability of the elements in such environments is one of the factors influencing their uptake. Entry routes into bodies of animals and human are through food, drink, air and dust particles. Arsenic levels in human blood, for instance, have been shown to correspond to the arsenic content of food consumed, especially fish.

Environmental impacts of geothermal energy utilization in Kenya have also been studied in a fair amount of detail for Olkaria geothermal field (Merz and McLellan - Virkir, 1977; Ewbank Preece Ltd., 1989; Tole, 1990; Sinclair Knight et al., 1992; Marani, 1994). Simiyu and Tole (1994) indicated that there can be an enrichment of elements in soils in contact with waste geothermal fluids in Olkaria area by factors up to 6000 for Zn; 500 for Cu; 240 for Pb; 125 for Cd; and 13 for B compared to waters with which the soils are in contact. In plants, the elements are concentrated by up to 7800 for Zn; 2250 for Cu; 625 for Pb; 259 for Cd and 13 for B in the case of green algae in direct contact with waste water. Other plants concentrate the elements by factors up to 1 for Cd and B; and 3 for Zn and Cu compared to green algae.

6.4 Field methods adopted

6.4.1 Preliminary survey

Prior to commencing the programme in 1993, a team comprising staff of the scientific section charged with the responsibility of coordinating environmental management in Olkaria geothermal project, a postgraduate student from the School of Environmental Studies of Moi University, Eldoret, and the then KPC's member of the Board of Consultants on environmental matters, carried out a detailed preliminary

survey in the Olkaria region to determine the most sensitive ecosystems of concern in the region which might be affected by geothermal activity. The survey included vegetation and land use, human population and proximity to the geothermal facilities, potential use of the lake, rivers and springs and those that might be receiving geothermal wastewater and effluents, identification of soil types with particular emphasis on clay minerals and their ability to adsorb and desorb nutrients and contaminants, terrestrial wildlife habitats and the predominant species including birds, mammals etc., with particular attention to native species for food and commercial purposes and those protected for recreation, and predominant aquatic wildlife including plants, invertebrates, and fish which are sensitive to change.

Locations and number of impact and control monitoring sites were selected and mapped with respect to the proximity to the potential sources of geothermal contaminants which include separated wastewater, condensate, effluents, stack and cooling tower emissions from the power plant facility, and gas or steam from discharging wells.

The types of environmental samples to be taken, mode and frequency of sampling and analytical methods to be adopted during the monitoring period were discussed and agreed upon. The environmental samples were to include geothermal fluids (liquid and gaseous components), potable water, soil and vegetation. The most recent and active parts of vegetation, i.e. leaves where active biological assimilation of nutrients and other chemicals is expected to dominate, were to be sampled. The frequency of sampling was to be every three months to cover seasonal variations in climatic conditions such as rainfall, temperature and surface water chemistry.

6.4.2 Location and number of sampling points

Thirty nine sampling points in total located in the Olkaria area and the surrounding regions were selected. Sixteen sampling points are at well sites referred to as Olkaria well (OW) within the Olkaria geothermal field of which ten, four, and two sampling well sites are within the Olkaria East production field (EPF), Northeast field (NEF) and Olkaria West field (OWF), respectively, and one site in Oserian Development Company Ltd., which is a horticultural farm bordering the field of operation. These were designated as impact stations. The well sampling sites are shown in Figure 1.

Ten other impact stations are located within the production field: Power station facilities (three sealpits, condensers and cooling tower units), three wastewater infiltration lagoons/ponds, four trial vegetable and flower plots, site camp and X-2 camp. The lagoons, trial plots and site camp are located a few metres away from the operating power plant, whereas the X-2 camp is within the Northeast field.

More so, six other stations: Lake Side and View estates, Lake Naivasha, Kongoni ranching farm, Kinja nursery, G.K. prison (located in Naivasha township about 45 km away from the geothermal field) are sited in the vicinity of the field as control stations. On the same basis, four rivers (Karati, Malewa, Gilgil, Ewaso Kedong), ten springs in Hell's gate gorge, and a domestic water borehole at Kinja in the vicinity were included in the monitoring programme.

Sampling was also carried out in three geothermal fields under exploration: Domes, Eburru, and Suswa. The aim was to acquire baseline data for the environmental significant chemical components and trace elements for future reference when development takes effect in the respective fields.

6.4.3 Sampling

The sampling techniques employed for the different environmental samples are the following:

Concentration of the elements in geothermal fluids and potable water: Brine, condensates, wastewater and potable water samples were collected into pre-washed 0.5 litre polythene bottles in triplicates. Samples were then taken to the laboratory for treatment and analysis.

Concentration of the elements in soil and sludge: Soil and sludge samples were collected in triplicates into polythene bags from a depth of 0.5-5 cm using plastic mugs, from the same sampling stations as brine, wastewater and potable water. Samples were then taken to the laboratory for treatment and analysis.

Concentration of the elements in vegetation: Plant leaves were collected in duplicates into polythene bags using a pen knife, from the same sampling stations as the soil samples. The samples were then taken to the laboratory for treatment and analysis.

6.5 Laboratory methods adopted

6.5.1 Analysis of geothermal fluids and potable water samples

The third bottle of the triplicate samples of the geothermal fluids and springs was cooled to ambient temperature in a cold water bath and immediately analysed for pH, and boron by the curcumin method using a spectrophotometer.

The 500 ml of fluids in the other two bottles were pre-concentrated 10 times by evaporation to 50 ml in a water bath at 90°C, with pH maintained at 9-10 by adding NaOH pellets to minimise deposition of silica. The concentrate was preserved at pH ranging from 1.5-2 (Upor, 1985) by adding 2.0 ml of conc. Nitric acid, for subsequent analysis of Zn, Cd, Pb, Cu, Li and Ba using an atomic absorption spectrophotometer (AAS). Similar treatment and analysis was accorded to potable water samples, omitting the cooling and addition of NaOH pellets procedures.

The elements were not analysed for immediately during the period of monitoring because of the unavailability of a graphite-carbon furnace and other flameless AAS equipment. Therefore, the preserved samples were analysed at the Mines and Geological Department, Nairobi for Zn, Cd, Pb, Cu, Li, and Ba. A few of the samples were analysed for As and Hg at the Government Chemists Department, Nairobi by an aspiration method using flameless AAS. F was analysed for using a selective ion electrode sensitive to F and a pH / mV metre. The F content of the samples was determined by directly comparing the sample response potential obtained to that of standard solutions of known F content. Comparison was then made by plotting readings on a semi-log graph paper. Standards and samples were diluted with an ionic strength adjustment buffer to maintain the pH of samples at 5-6, to destroy complexes and to adjust these to the fixed ionic strength.

The AAS was preferred because of its high accuracy and precision, and its sufficiently low detection limits for most of the trace elements in environmental and biological samples.

6.5.2 Analysis of soil samples

One of each of the triplicate samples was sun dried to a constant weight for 96 hours. The dried sample was prepared and its pH determined by the soil-pH measured-in-water method (Black, 1965). Each of the remaining two samples was sprayed with 0.1 N NaOH, to prevent loss of B (Upor, 1985) during drying and oven dried to constant weight at 95°C for 48 hours. 2.0 gm of each of the dried soil samples, size fraction 400 μm , were extracted by the wet extraction method using aqua regia (Upor, 1985; Chale, 1990). The extract, stored in clean 100 ml plastic bottles, was then analysed for the trace elements as geothermal brine, wastewater and potable water.

6.5.3 Analysis of vegetation materials

Each of the plant and soil samples collected was washed with deionized water and sprayed with 0.1 N NaOH before being dried. The samples were oven dried to constant weight at 95°C for 48 hours. The dried samples were prepared and extracted for analysis as the soil samples.

6.5.4 Reagent blanks

The blanks were given the same treatment as the samples. For example, blanks for water analysis were prepared by measuring 500 ml of deionized water into a clean 500 ml beaker and adding NaOH pellets to maintain pH at 9-10. This was pre-concentrated 10 times by evaporation to 50 ml in a water bath at 90°C. The blank concentrate was allowed to cool to room temperature and 2.0 ml of concentrated nitric acid added to maintain pH at 1.5-2.0.

The blanks for soil and plant samples analysis were prepared in the same way as the soil and plant samples. The blanks so prepared were stored in clean 100 ml plastic bottles for analysis.

6.6 Results and discussion

6.6.1 Environmental analytical data

Detailed data analysis of mean values, deviations, covariance, and types of errors were performed as part of the environmental data validation and quality management. Then the available four sets of data were screened for consistency in quarterly sampling for water, soil, and vegetation materials with respect to the aforementioned impact and control monitoring locations. The results presented are for the selected sites with slight variations from one sampling quarter to the other over the entire monitoring period ranging from 1996 to 1998. The presented analytical data for Hg and As are not discussed as the flameless AAS aspiration method used gave inconsistent analytical results, probably due to its insensitivity to the elements, particularly in environmental or biological samples. Likewise, results for B are ignored due to the inconsistency in analysis during the period of monitoring considered.

The selected analytical data are presented in Appendix 1 (see Tables 1-4). They include the average/mean values for 1996, the second quarter/June and third quarter/September, 1997, and the first quarter/March, 1998, after carrying out basic statistical analysis to determine the mean values of the concentration measurements for each element in the three media under monitoring.

6.6.2 Concentration levels of trace elements in geothermal fluids, potable water, soil and vegetation

Graphical representation of concentration levels at the monitoring locations for each of the elements in water, soil and vegetation in 1996, 1997, and 1998 are as shown in Figures 5-8.

Zn, Pb, Li, and F occur in significant amounts in geothermal well discharge water. Geothermal wastewater in the lagoons, however, shows comparatively low levels of these elements except for F. Cd levels are also rather low.

The levels of Zn, Cd, Cu, and Ba in geothermal fluids during the monitoring period are within the optimum limits of national (Kenya Bureau of Standards) and international (World Health Organization) standard quality criteria for water and wastewater. This is not the case for Pb, Li, and F. The highest concentrations detected for the three elements were Li - 1.86 ppm, Pb - 0.6 ppm, and F - 10.35 ppm in separated well water from OW-21 in East production field, and well 101 in ODC Ltd,. However, the Li level recorded is still below the recommended level of 2.5 ppm for irrigation and livestock watering (Brown, 1995). Moreover, Li causes no adverse effects on human and aquatic life, although cases of severe toxicity on citrus plants has been observed.

Aquatic life may be harmed at Pb concentrations above 0.1 ppm. However, toxic effects on fish vary depending on the type and mineral content of the water. Apart from that, Pb concentrations in water are

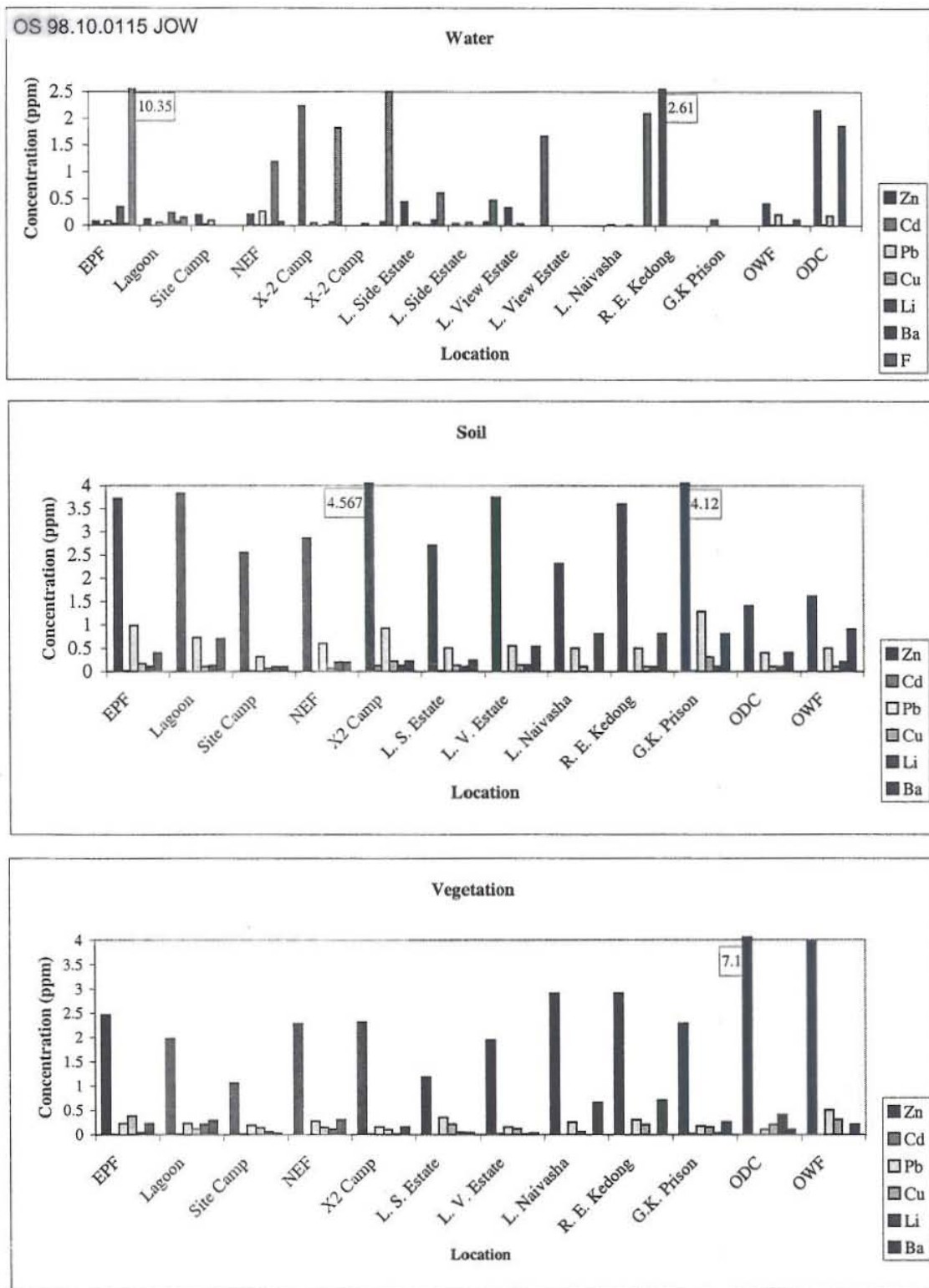


FIGURE 5: Concentration levels of trace elements in the Olkaria geothermal field in 1996

considered for aesthetic characteristics of water only. Zn, Cu, Ba, and F are common elements detected in potable water sources that include both raw and chemically treated water for domestic consumption. With the exception of F, levels are low in comparison to those of geothermal wastewater. However, the levels of all the elements in both raw and treated potable water sources are within the recommended optimum health limits for drinking, stock watering, irrigation, and aquatic life protection with the exception of F. The highest concentration value for F recorded is 2.09 ppm for Lake Naivasha.

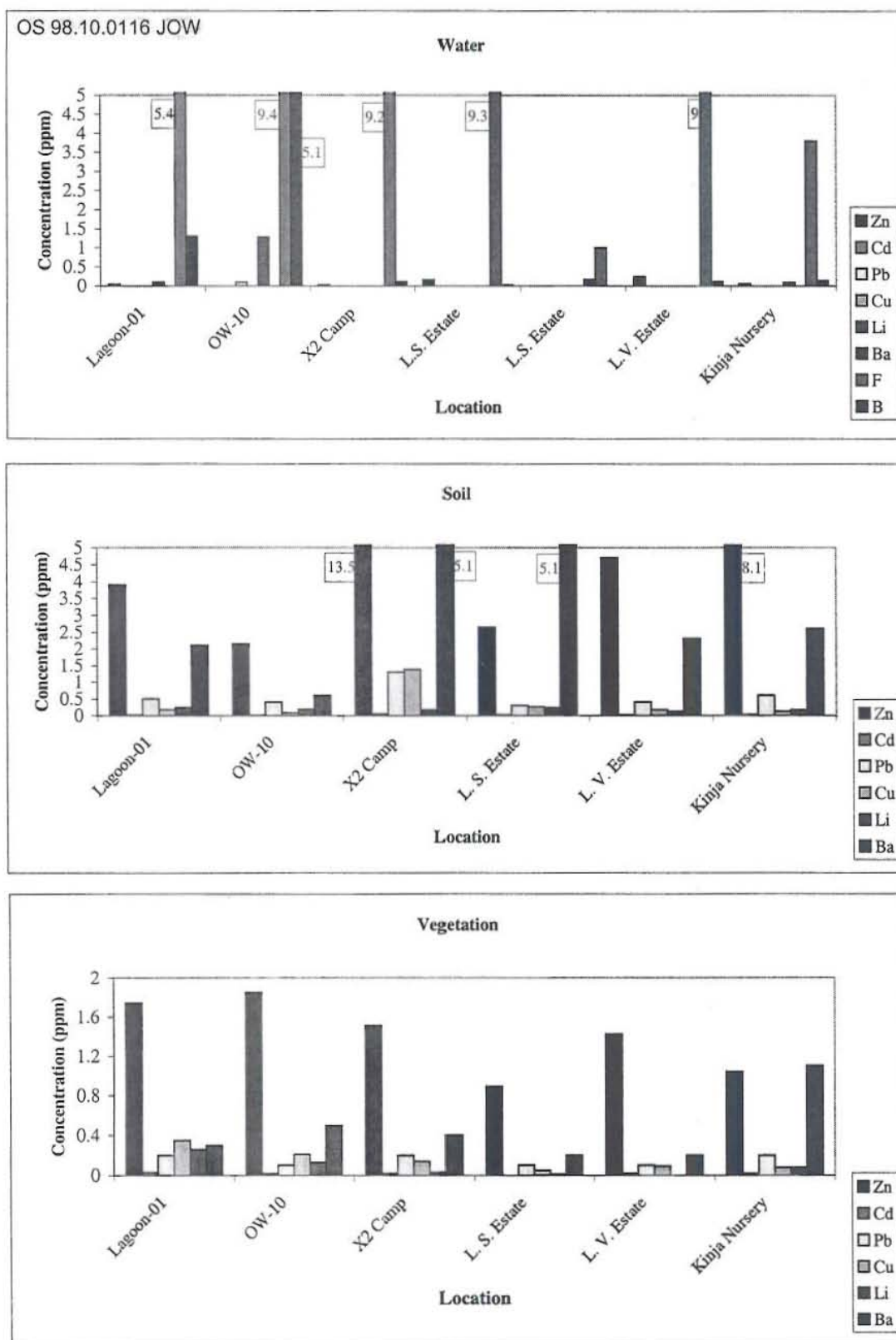


FIGURE 6: Concentration levels of trace elements in the Olkaria geothermal field in 2nd quarter / June, 1997

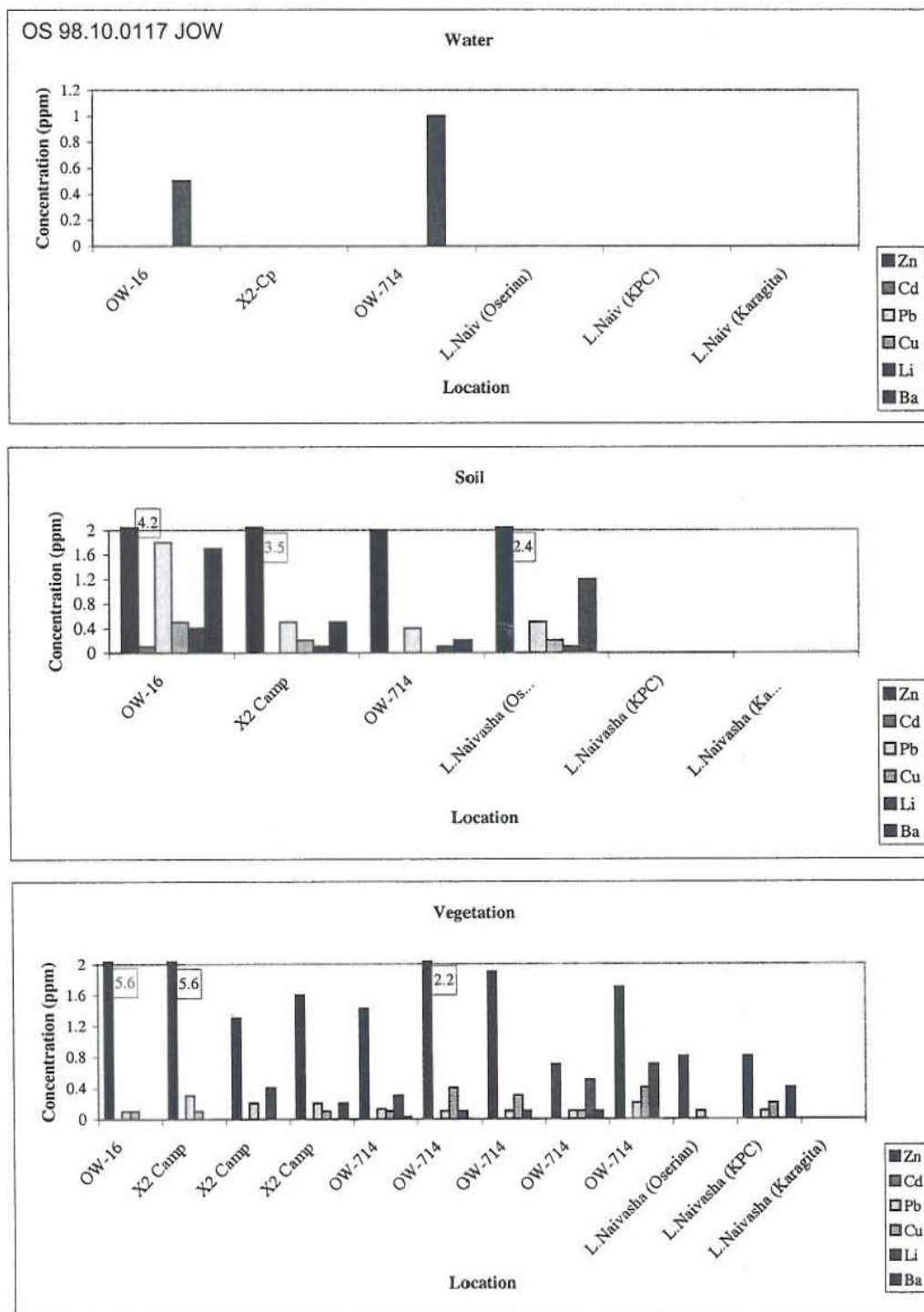


FIGURE 7: Concentration levels of trace elements in the Olkaria geothermal field in 3rd quarter / September, 1997

The F concentration of surface waters rarely exceeds 1.5-1.6 ppm, the maximum recommended concentration for domestic water supplies when temperatures are 22-26°C. The Kenyan Rift Valley waters have exceptionally high concentrations of F, as confirmed by the monitoring results. Geothermal waters, however, commonly exceed recommended water quality criteria for dissolved fluoride and could constitute a source of potential F contamination to natural waters (Nordstrom and Jenne, 1976). Nevertheless, low and stable levels (0.5-1.7 ppm) of dissolved F are required to maintain dental health, prevent teeth mottling in children and prevent fluorosis in livestock.

Otherwise, toxicity of elements such as Zn and Cu to aquatic life is related to similar factors as that of Pb above, in addition to dissolved oxygen, carbon dioxide, calcium, magnesium, temperature, etc.. The

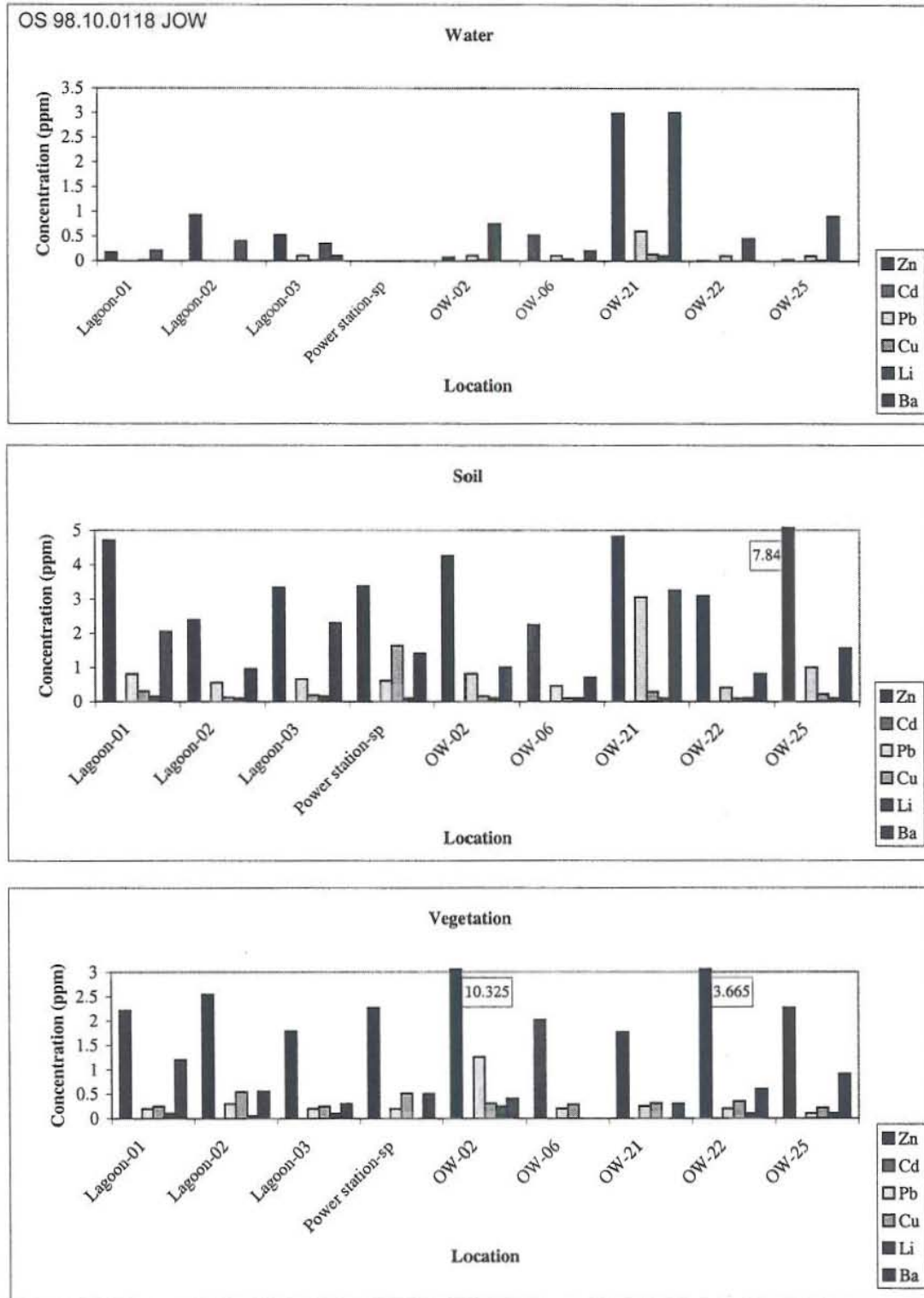


FIGURE 8: Concentration levels of trace elements in the Olkaria geothermal field, in 1st quarter / March, 1998

tolerable amount of Zn in drinking water is limited to an unpleasant taste at 5-10 ppm, whereas Cu concentration of 4-5 ppm and above in water imparts a metallic and stringent flavour. The toxicity of Cu is relatively low and, therefore, relatively high concentrations are specified as Cu is ingested everyday with food.

All the six trace elements considered in the report occur in detectable amounts in soil with Zn, Pb and Ba showing significant levels, followed by Cu and Li which are more or less of the same level of

concentration. Cd is at low levels but is often detected in soils around the lagoons and sparingly around well sites. A similar concentration level pattern is evident at all the monitoring sites including those outside the Olkaria geothermal field. Higher levels of some of the elements such as Zn (> 5.0 ppm) and Pb (> 1.0 ppm) have been recorded in control monitoring sites i.e., in G.K prison, Naivasha Township.

The concentration levels of the elements in vegetation are slightly lower than in soil. Zn occurs at significant levels whereas the rest of the metals rarely exceeds a concentration level of 1.0 ppm, with the exception of Ba and Pb in vegetation of lagoon and East production field well OW-02. A similar concentration pattern as for soils is evident for both impact and control monitoring sites. Nevertheless, vegetation around wells that have undergone a discharge test for about a month, such as well OW-714 in Northeast field shows significant levels of Li and Pb, and slightly elevated levels of Cu and Ba.

The concentration levels of Zn, Cd, Pb, and Cu, in both soil and vegetation are, however, below the optimum limits above which these environmental components are said to be contaminated or polluted. (National Agricultural Laboratory, Kenya). The highest concentrations recorded in soil are as follows: Zn - 13.5 ppm, Cd - 0.123 ppm, Ba - 5.1 ppm, Pb - 3.05 ppm, Li - 0.4 ppm and Cu - 1.63 ppm, in X2 Camp (Zn, Cd, and Ba), East production field wells OW-21, and OW-16, and sealpits of the power station, respectively. The highest concentrations recorded in vegetation are as follows: Zn - 10.325 ppm and Pb - 1.25 ppm, Cd - 0.03 ppm and Ba - 1.2 ppm, Cu - 0.54 ppm and Li - 0.7 ppm in East production field well OW-02, Lagoon-01, Lagoon-02 and Northeast field well OW-714, respectively.

Due to a lack of limit values for Li and Ba in soil and vegetation, the status of detected levels of concentration for Li (0.4 ; 0.7 ppm) and Ba (5.1 ; 1.2 ppm) could not be ascertained with respect to environmental pollution.

Soils have a strong capacity for fixing Pb, with the formation of Pb humic complexes which are less toxic. Moreover, plant varieties are also rather tolerant to Pb taken up from soil. However, in agriculture, Zn levels as low as 5.0 ppm in soil may induce withering in some plant varieties.

Though Cd often occurs at levels below detection limits, it is highly toxic as it results in kidney and enzymatic anomalies, which may impede the transport of iron. Likewise, Ba is poisonous to muscle cells and affects cardiac muscles and vascular walls.

6.6.3 Status of enrichment trace elements in the Olkaria area and its precincts

Graphic plots of concentration levels for each of the elements in all of the three media in an attempt to verify the possibility of elevated levels of contamination for trace elements are indicated in Figures 9-11.

Soil in contact with geothermal waste fluids has elevated levels by factors of 261(Zn), 5 (Pb), 2 (Cu), and 1 (Ba) in East production field wells OW-25 and OW-21. Similarly, soil in contact with potable water sources shows elevated levels by factors of 4 (Cd) 3 (Pb), 43 (Zn), 20 (Cu), and 800 (Ba) in X2 Camp, the first and the last two in Site Camp, and L. Naivasha, respectively. However, the level of Li in soil is quite variable, irrespective of the nature of the water in contact over the monitoring period.

Vegetation showed elevated levels by factors of (137 ; 1) for Zn, (12 ; 2) for Pb, (14 ; 10) for Cu, (8 ; 13, 000) for Ba and (1 ; 2) for Cd, in geothermal fluids of OW-02 and Northeast field and potable water sources of X2 and Site Camps, L. Naivasha, and G.K prison in Naivasha township, respectively. Li levels are notably variable as in the case of soil above.

Further factor analysis for soil and vegetation components in the East production field, Northeast field, and infiltration lagoons/ponds based on 1996 analytical data are as indicated in Table 5.

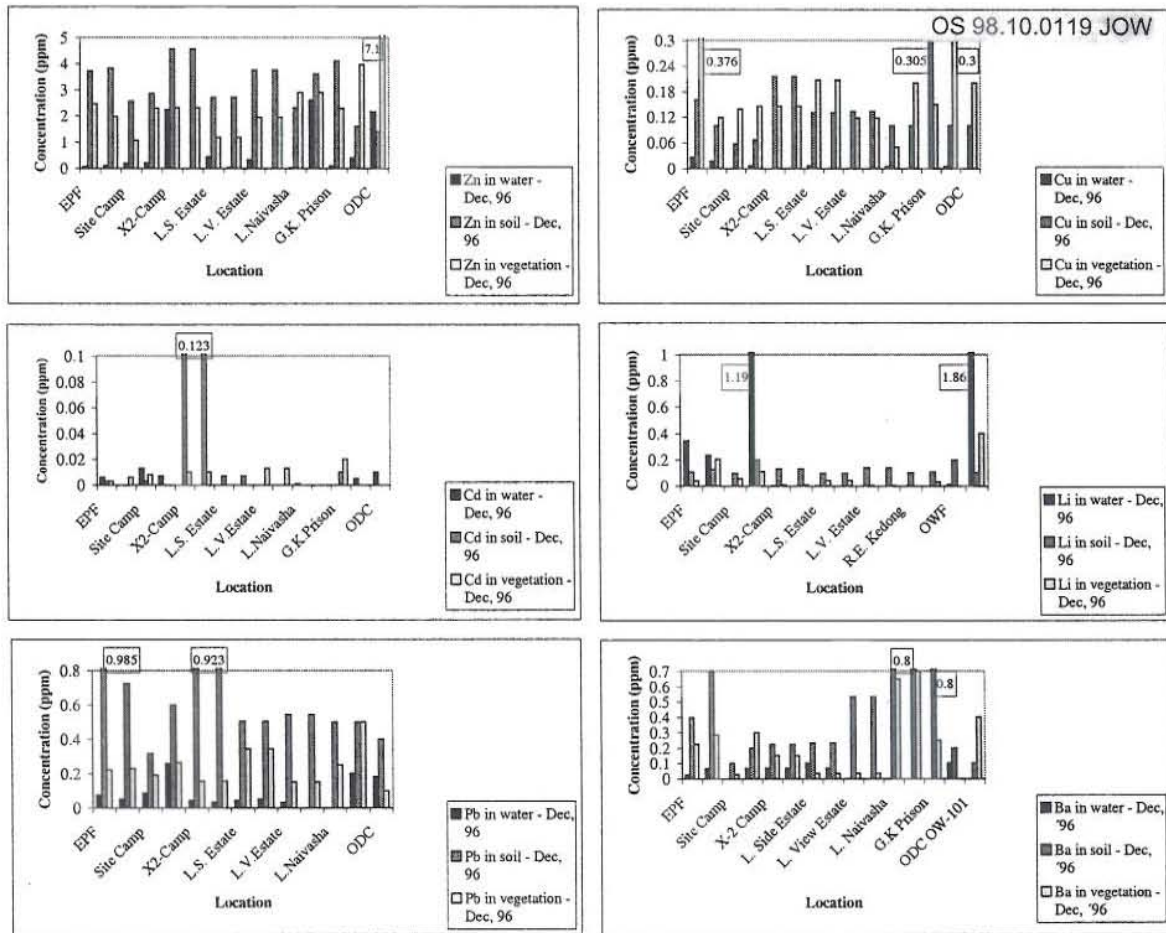


FIGURE 9: Comparison of concentration levels of trace elements in different media in the Olkaria geothermal field, in 1996

TABLE 5: Factor analysis of concentration levels of elements in soil and vegetation with different impacts of geothermal fluids

Parameters	Zn	Cd	Pb	Cu	Li	Ba
Soil						
Olkaria East production field	52	0.5	12	6	0.3	15
Infiltration lagoons	35	0 (<dl)	14	6	0.5	10
Olkaria Northeast field	14	0 (<dl)	2	10	0.2	3
Vegetation						
Olkaria East production field	35	0.5	3	14	0.1	9
Infiltration lagoons	18	0.006	5	7	0.9	4
Olkaria Northeast field	11	0 (<dl)	1	19	0.09	4

<dl : Less or below detection limit

It is worth noting the potential and capability of vegetation of natural infiltration wastewater lagoons to accumulate all the trace elements to higher levels by considerable factors. The levels of the detected elements such as Zn, Cd, Pb and Ba, however, are far below the limits above which soil and vegetation media are said to be polluted. Therefore, this study shows no significant level of contamination or pollution in soil, sludge and vegetation in the Olkaria geothermal field.

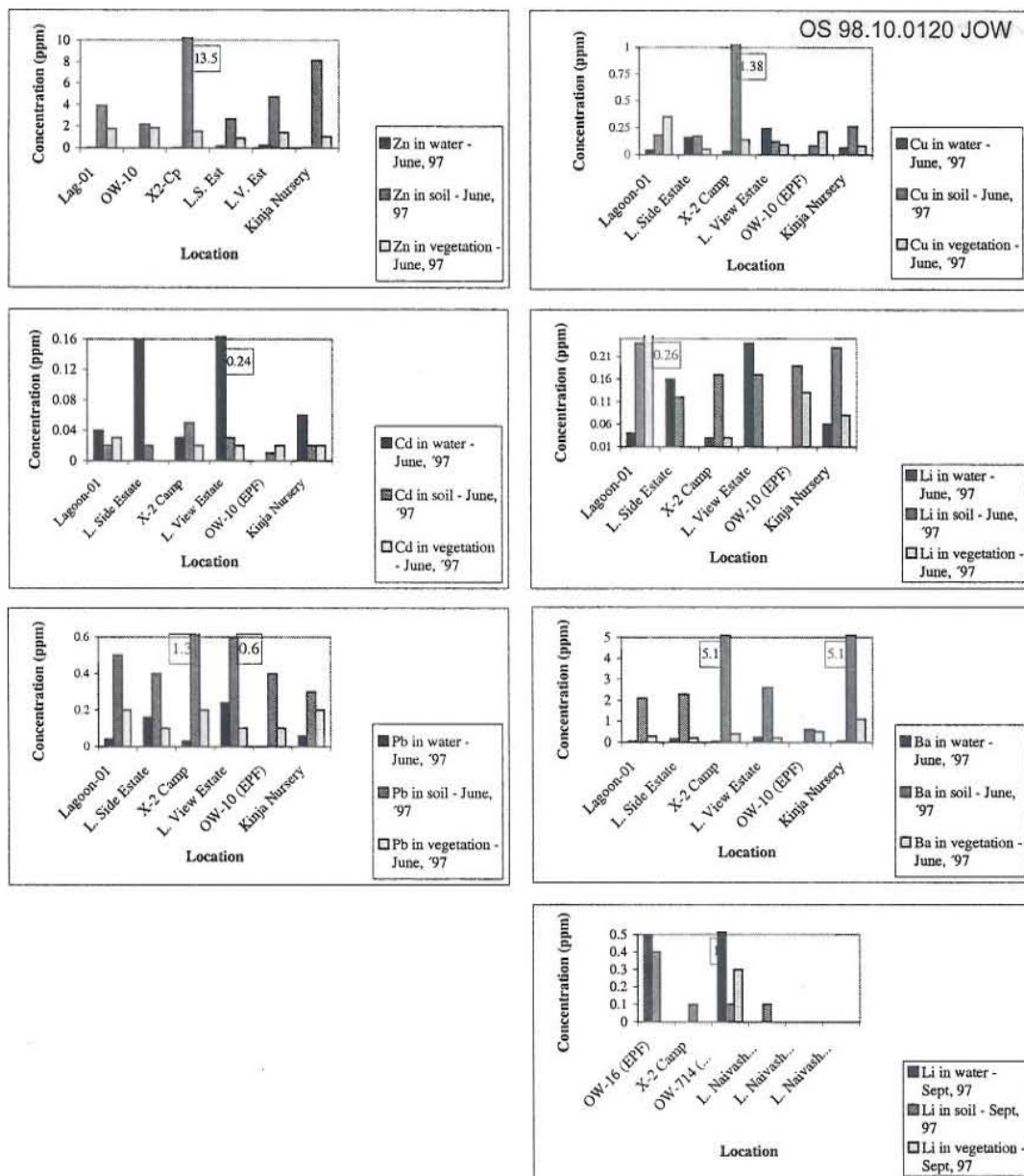
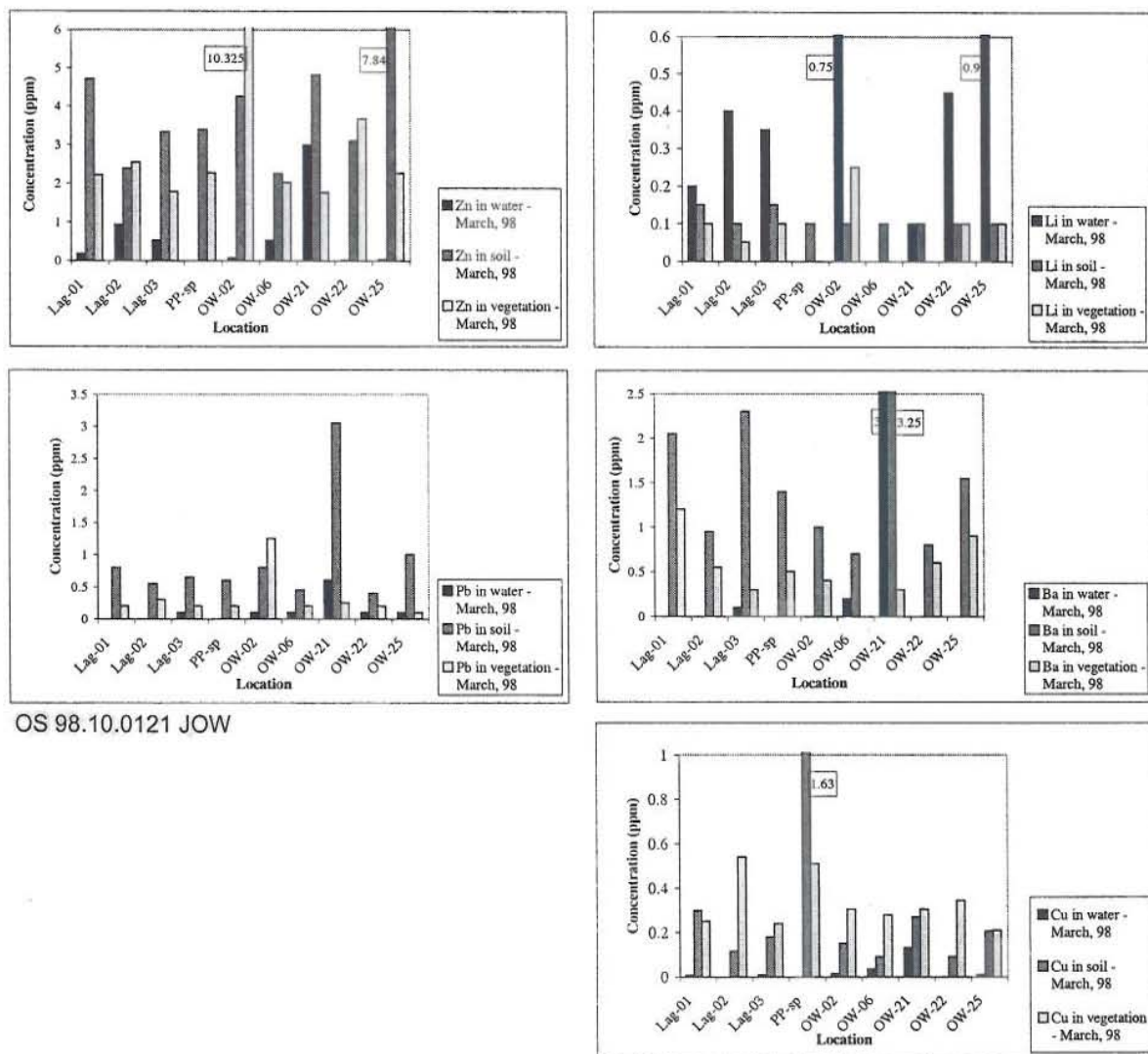


FIGURE 10: Comparison of concentration levels of trace elements in different media in the Olkaria geothermal field, in June and September 1997

6.6.4 Trend of concentration levels of trace elements in the operational Olkaria East production field

Elemental trend analysis in geothermal fluid, soil, and vegetation for the operational Olkaria East production field during the period of monitoring is depicted in Figure 12. The aim was to ascertain the nature of the variations in elemental concentration levels with time to enhance predictions of possible effects of seasonal variations in climatic conditions such as rainfall, temperature and water chemistry. However, no trends were obtained as covariance between results of each quarter was very small. The variations for elements such as Li in geothermal fluids and Zn in vegetation, could be procedural variations. Hence, predictions of the seasonal and possible future status of chemical contamination or pollution in Olkaria geothermal field could not be effected. However, the data interpretation procedure is essential and needs to be perfected in future.



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FIGURE 11: Comparison of concentration levels of trace elements in different media in the Olkaria geothermal field, in March 1998

6.6.5 Spatial distribution of trace elements in the Olkaria geothermal area and outlying regions

Contour maps of mean elemental concentrations in soil and vegetation based on analytical data for 1996 for four monitoring locations within and outside Olkaria geothermal field are as shown in Figures 13-14.

The homogenous spatial distribution pattern of the chemical elements in the two environmental components depicts no clear and certain immediate influence from the exploitation of the geothermal resource of the Olkaria geothermal field and its surrounding regions. Natural and other anthropogenic sources apart from geothermal resource exploitation, could be responsible for the levels recorded in the monitoring stations. In any case, the region monitored is within the rift zone with similar geological and volcanic history. Other factors such as emissions from traffic along the roads could also be considerable. For example, the level of Pb in soil and vegetation in Naivasha township could be due, among other sources, to emissions from heavy traffic along the Trans-African highway crossing the town.

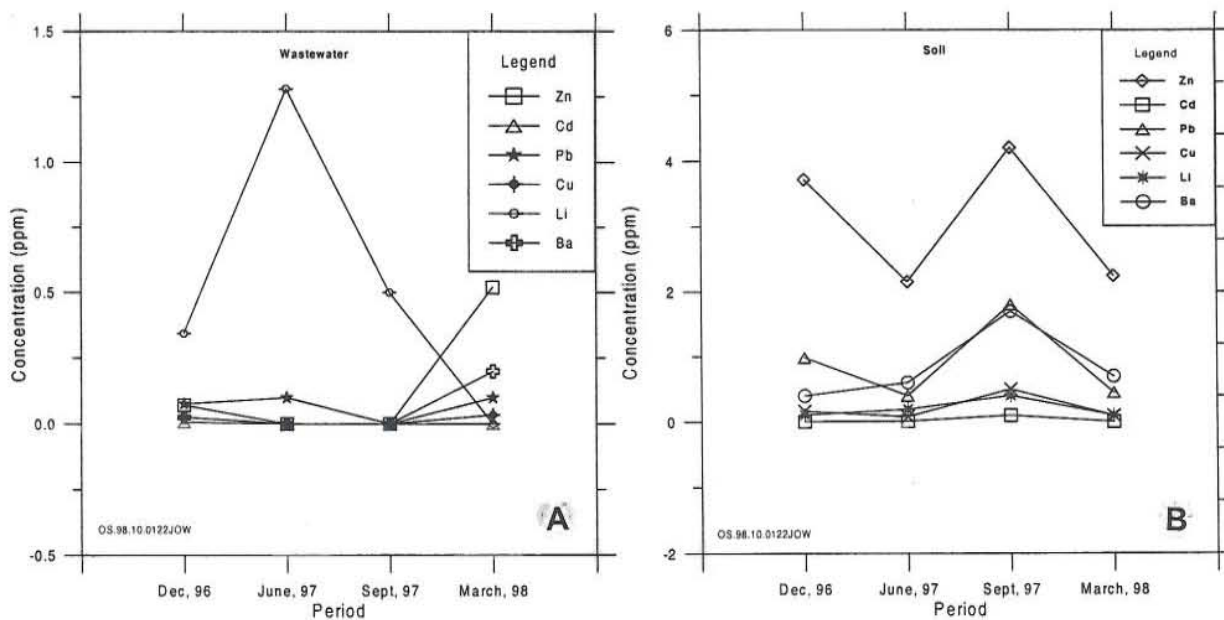
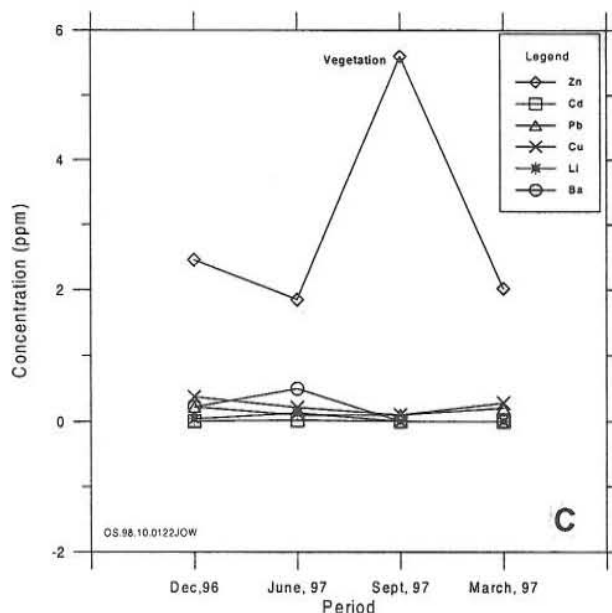


FIGURE 12: Trend of elemental concentration levels in the operational Olkaria East production field in 1996-1998; a) Geothermal wastewater; b) Soil; and c) Vegetation

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

1. The concentration levels of the chemical elements monitored in Olkaria geothermal field are within the national and international optimum health limits and quality guidelines except for Pb, Li, and F in geothermal waste fluids. Levels of the monitored elements in potable water are all within acceptable optimum health limits and quality guidelines with the exception of F. Soil, sludge, and vegetation have slightly elevated levels of the detected elements. However, the levels determined are still far below limits for polluted soil and vegetation.
2. Geothermal waste fluids could be a potential source of toxic geothermal chemical components and trace elements, particularly in soil, sludge, and vegetation materials within Olkaria geothermal field, aside from other natural sources of the trace elements.
3. There is no significant environmental chemical contamination caused by the monitored elements in Olkaria geothermal field and the adjacent regions. In this respect, exploitation of geothermal energy resources in the region can be said to be environmentally sustainable.



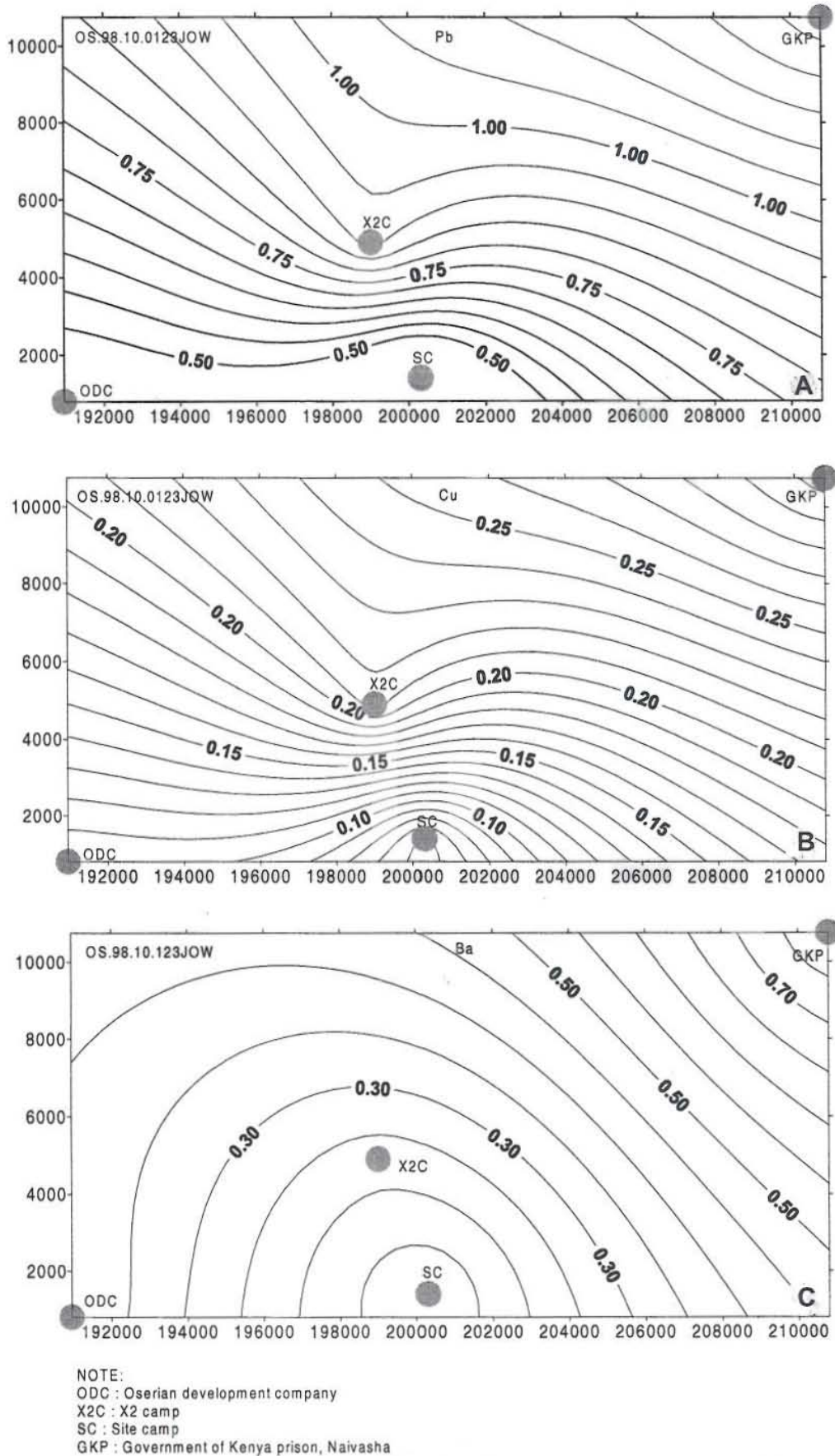


FIGURE 13: Concentrations in soil of the Olkaria area and outlying regions; a) Lead; b) Copper; and c) Barium

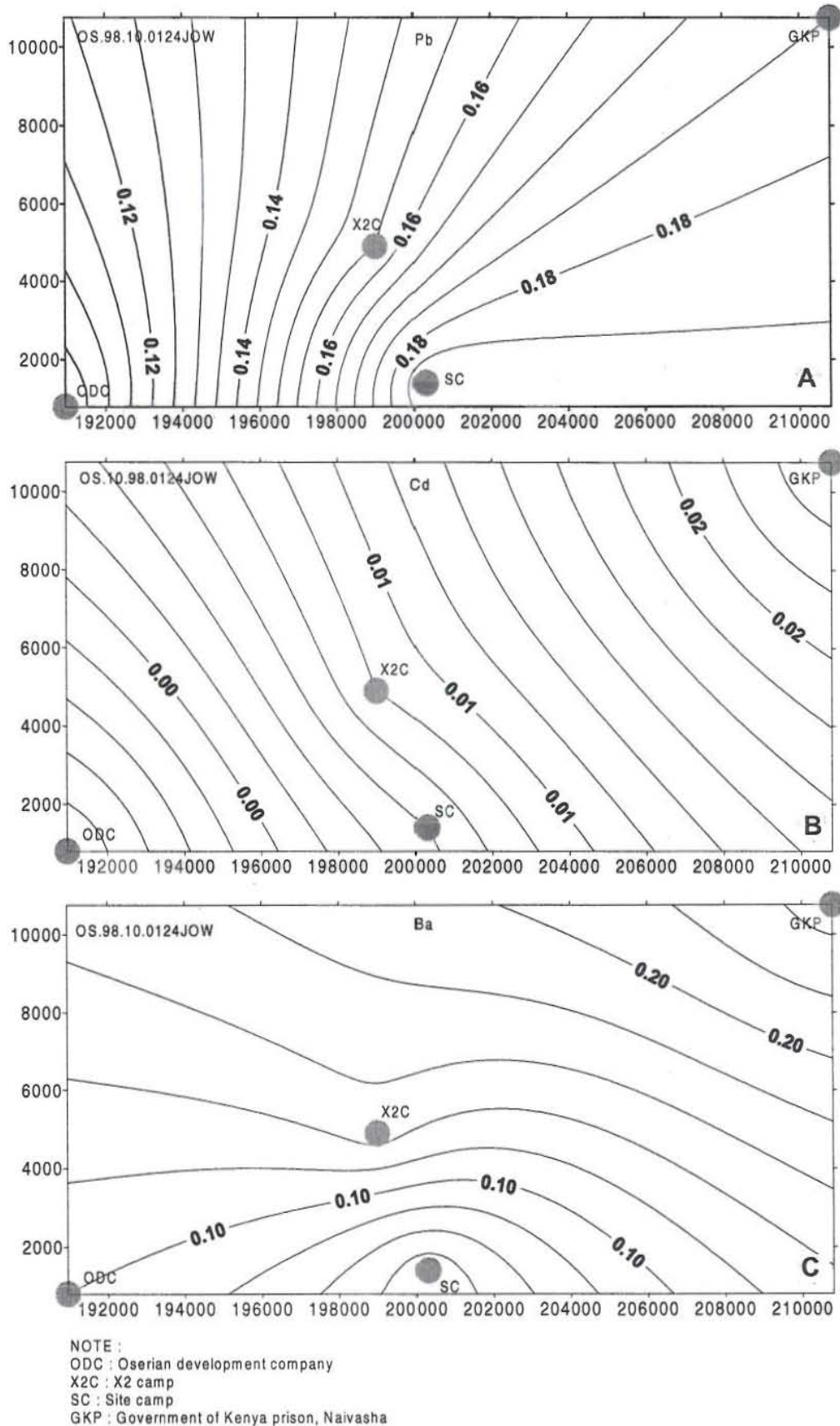


FIGURE 14: Concentration in vegetation of the Olkaria area and outlying regions; a) Lead; b) Cadmium; and c) Barium

7.2 Recommendations

1. Fluoride level in potable water and geothermal waste fluids, is considerably high. Likewise, Pb and Li levels in geothermal fluids are slightly above optimum health limits. Hence, the need is for further monitoring and research on their impacts on the biosphere.
2. Deep reinjection of the discharged geothermal wastewater is recommended. Careful monitoring of the effects on production zones is essential.
3. The duration of discharge testing of wells needs to be reviewed and, if possible, minimised to curtail emissions of the elements through aerosols.
4. Vegetation flourishing adjacent to the stabilizing and infiltration lagoons/ponds should be fenced off completely to keep animals from feeding on them and, thus, enhancing the potential of bioaccumulation of some of the chemical elements to highly toxic levels up the complex biological food chain.
5. Parallel uses of the geothermal waste fluids after electricity generation should be investigated for Olkaria geothermal field and, if possible, made an integral part of the power station to maximise the use of geothermal heat.
6. The potential and performance of the infiltration lagoons in the East production field as a "Wetland" for wastewater treatment, should be investigated and, if viable, adopted as a wastewater management process in addition to the widely acceptable deep reinjection disposal method.
7. Soil, sludge, and scale from operational activities should be disposed of in landfills or dumping sites which must be covered with ordinary soil and rehabilitated.
8. The geothermal waste fluids should be collected through pipes and the effluents from the power station by gravitational flow in gravel sealed channels into the pond before reinjection, to reduce possible adsorption of elements into soil.
9. Monitoring of concentration levels of trace elements and a study of their possible biological impacts on humans, flora, and fauna, should be adopted as a routine programme to ensure that geothermal energy is exploited in an environmentally sustainable manner with maximum benefits.
10. For future reference, it is recommended that baseline data on environmentally significant geothermal chemical components and trace elements be established for potential geothermal fields and those under exploration, i.e. Domes, Eburru, Suswa, Longonot.

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REFERENCES

- Ármansson, H., 1997: *Reykjanes, a preliminary investigation for environmental assessment*. Orkustofnun, Reykjavík, report OS-97031 (in Icelandic), 58 pp.
- Ármansson, H., and Kristmannsdóttir, H., 1992: Geothermal environmental impact. *Geothermics*, 21-5/6, 869-880.
- Batley, G., 1996: *Water quality management in power stations*. Issue of interface, Energy Technology, CSIRO, Australia, November, 1996, web@det.csiro.au.
- Black, C.A., 1965: Methods of soil analysis. *Agronomy J.*, 9-2.
- Bogarín C., R., 1996: Geothermal gases as a source of commercial CO₂, in Miravalles, Costa Rica and Haedarendi, Iceland. Report 3 in: *Geothermal Training in Iceland 1996*. UNU G.T.P., Iceland, 23-44.
- Bodry, A., 1991: Council directive of 18th march 1991, amending directive 75/442/EEC on waste. *Official Journal of the European Communities*, No. L 78/32.
- Brown, K.L., 1995: Impacts on the physical environment. In: Brown, K.L (convenor), *Environmental aspects of geothermal development*. World Geothermal Congress 1995, IGA pre-congress course, Pisa, Italy, May 1995, 39-55.
- Clarke, M.C.G., Woodhall, D.G., Allen D., and Darling, G., 1990: *Geological, volcanological and hydrogeological controls on the occurrence of geothermal activity in the area surrounding Lake Naivasha, Kenya*. Ministry of Energy, Republic of Kenya, report, 138 pp.
- Dormuth, K.W., Gillespie P.A., and Whitaker, S.H., 1995: Disposal of nuclear fuel waste. In: Hester, R.E., and Harrison, R. M. (editors), *Issues in Environmental Science and Technology*, No. 3, *Waste treatment and disposal*, 115-118.
- El Hinnawi, E., and Biswas, A.K., 1981: Renewable sources of energy and the environment. In: El Hinnawi, E. (editor), *Environmental impacts of production and use of energy*. An assessment prepared for the United Nations Environmental Programme, Tycooly Intern. Publishing Ltd., Dublin, 27-50.
- Ellis, A.J., 1975: *Environmental impacts of geothermal utilization*. Report prepared for the United Nations Environmental Programme, UNEP, 62 pp.
- Eugene, C.C., 1998: *Health care waste management within hospitals*. Document prepared at the request of the WHO regional office for Europe, European Centre for Environment and Health, Nancy project office.
- Ewbank Preece Ltd., 1989: *Feasibility study for a geothermal power station at NE Olkaria - final report*. Prepared by Ewbank Preece Ltd. Consulting Engineers, Prudential House, Brighton, job ref. 80216.
- Fridleifsson, I.B., 1997: Worldwide status of geothermal development and international cooperation. *Geoth.. Res. Counc., Transactions*, 21, 347-353.
- Fridleifsson, I.B., and Freeston, D.H., 1993: Geothermal energy research and development. *Geothermics*, 23-2, 175-214.
- Marani, M., 1994: *Spatial temporal characteristics of H₂S concentration levels around the Olkaria geothermal power plant*. MPhil. thesis in environmental studies, School of Environmental Studies, Moi University, Eldoret, Kenya.

Merz & McLellan - Virkir, 1977: *Report on geothermal development at Olkaria*. Report prepared for the Kenya Power Company Ltd.

Nakahara, H., 1978: Environmental effects of geothermal waste water on the nearby river systems. *J. Radioanal. Chem.*, 45, 25-36.

Nordstrom, D.K., and Jenne, E.A., 1976: Fluorite solubility equilibria in selected geothermal waters. *Geochim. Cosmochim. Acta*, 41, 175-188.

Nriagu, J.O., 1989: A global assessment of natural sources of atmospheric trace metals. *Nature*, 338, 47-49.

Ofwona, C.O., 1996: Analysis of injection and tracer tests data from the Olkaria-East geothermal field, Kenya. Report 10 in: *Geothermal Training in Iceland 1996*. UNU G.T.P., Iceland, 197-218.

Pacyna, J.M., 1988: Quantitative assessment of world wide contamination of air, water and soils by trace metals. *Nature*, 333, 134-139.

Peralta, G.L., Kirk, D.W., Graydon, J.W., and Seyfried, P.L., 1998: Assessing the environmental impacts of geothermal residues. *Waste Management and Research*, 16-3, 225-232.

Reay, P.F., 1972: Accumulation of arsenic from arsenic rich natural waters by aquatic plants. *J. Appl. Ecol.*, 9, 557-565.

Ritchie, J.A., 1961: Arsenic and antimony in some New Zealand thermal waters. *N.Z. J. Sci.*, 4, 218-229.

Simiyu, G.M., and Tole, M.P., 1994: *Levels of selected trace elements in Olkaria geothermal fluids and their implications to the environment*. MPhil. thesis in environmental studies, School of Environmental Studies, Moi University, Eldoret, Kenya.

Sinclair Knight, ESA Pty Ltd, Sidney and RPS International Ltd, Nairobi, 1992: *Environmental assessment for North East Olkaria power development project*. Report prepared for Kenya Power Company Limited, KPC.

Skinner, B.J., White, D.E., Rose, H.J., and Mays, R.E., 1967: Sulfides associated with the Salton Sea geothermal brine. *Econ. Geol.*, 62, 316-330.

Thors, S.G., Hreggvidsdóttir, H., and Thoroddsson, Th.F., 1998: *Training course on environmental impact assessment*. Course material by the UNU Geothermal Training Programme, the Planning Agency of Iceland, and VSO Consulting.

Tole, M.P., 1990: Environmental effects associated with the use of geothermal energy. *Discovery and Innovation*, 2-3, 23-26.

Wambugu, J.M., 1996: Assessment of Olkaria-Northeast geothermal reservoir, Kenya based on well discharge chemistry. Report 20 in: *Geothermal Training in Iceland 1996*. UNU G.T.P., Iceland, 481-509.

Webster J.G., and Timberley, M.H., 1995: Chemical impacts of geothermal development. In: Brown, K.L (convenor), *Environmental aspects of geothermal development*. World Geothermal Congress 1995, IGA pre-congress course, Pisa, Italy, May 1995, 97-117.

Weisberge B.G., and Zobel, M.G.R., 1973: Geothermal mercury pollution in New Zealand. *Bull. Environm Contamination and Toxicology*, 9, 148-155.

APPENDIX 1: The environmental analytical data for the Olkaria geothermal field

TABLE 1: Average concentration of trace elements in the Olkaria geothermal field for 4th quarter / December, 1996.

No.	Location	Nature	pH	Zn	Cd	Pb	Cu	Li	Ba	As	Hg	F	B
Water													
		Optimum limits	6.5-8.5	5	0.01	0.05	1	0.25	1	0.05 (0.002)	0.005	1.5	1
1	EPF	Water (well)	8.1-10.1	0.071	0.006	0.076	0.026	0.345	0.026	0.136	0.003	10.35	
2	Lagoon	Water (waste)	3.14-8.99	0.11	0 (<dl)	0.05	0.017	0.233	0.067	0.02	0.013	0.148	
3	Site Camp	Water (ptw)	7.5	0.193	0.013	0.087	0 (<dl)	0 (<dl)	0 (<dl)				
4	NEF	Water (well)	8.5-9.7	0.203	0.007	0.26	0.007	1.19	0.067				
5	X-2 Camp	Water (ptw)	5.3	2.24	0 (<dl)	0.043	0 (<dl)	0.003	0.067	0.003	0 (<dl)	1.83	
6	X-2 Camp	Water (prw)		0 (<dl)	0 (<dl)	0.033	0 (<dl)	0 (<dl)	0.067	0.001	0 (<dl)	2.5	
7	L. Side Estate	Water (ptw)	7.3	0.44	0 (<dl)	0.043	0.007	0.003	0.1	0.001	0 (<dl)	0.6	
8	L. Side Estate	Water (prw)	9.3	0.033	0 (<dl)	0.05	0 (<dl)	0 (<dl)	0.067	0.002	0 (<dl)	0.467	
9	L. View Estate	Water (ptw)	7.9	0.327	0 (<dl)	0.03	0 (<dl)	0 (<dl)	0 (<dl)	0 (<dl)	0.001	1.67	
10	L. View Estate	Water (prw)						0 (<dl)					
11	L. Naivasha	Water (prw)	7.5-9.1	0.016	0.001	0.001	0.005	0 (<dl)	0.001	0.001	0.0001	2.09	
12	R. E. Kedong	Water (prw)	7.9	2.61	0 (<dl)	0 (<dl)	0 (<dl)	0 (<dl)	0 (<dl)				
13	G.K Prison	Water (ptw)		0.1	0 (<dl)	0 (<dl)	0 (<dl)	0 (<dl)	0 (<dl)				
14	OWF	Water (well)	7.4-8.1	0.41	0.005	0.2	0.005	0.01	0.1				
15	ODC	Water (well)	9.5	2.15	0.01	0.18	0 (<dl)	1.86	0 (<dl)				
Soil													
		Optimum limits		5.0 (300)	0.1-1	10.0-40.0	1.0-20.0 (100)	na	na	1	1		5.0- 30.0
16	EPF	Soil	3.0-9.8	3.72	0.003	0.985	0.161	0.105	0.398	0.011	0.018		
17	Lagoon	Soil	7.1	3.83	0 (<dl)	0.725	0.1	0.125	0.7	0.028	0.075		
18	Site Camp	Soil		2.55	0.003	0.317	0.057	0.097	0.1				
19	NEF	Soil		2.86	0 (<dl)	0.6	0.067	0.2	0.2				
20	X-2 Camp	Soil	5	4.567	0.123	0.923	0.215	0.13	0.223	0.0002	0.0001	0 (<dl)	
21	L. Side Estate	Soil	5.3	2.7	0.007	0.503	0.13	0.097	0.233				
22	L. View Estate	Soil	2.8	3.75	0 (<dl)	0.543	0.133	0.137	0.533				
23	L. Naivasha	Soil	7.7	2.3	0 (<dl)	0.5	0.1	0 (<dl)	0.8				
24	R. E. Kedong	Soil	6.7	3.6	0 (<dl)	0.5	0.1	0.1	0.8				
25	G.K Prison	Soil	3.4	4.12	0.01	1.28	0.305	0.105	0.8				
26	ODC	Soil		1.4	0 (<dl)	0.4	0.1	0.1	0.4				
27	OWF	Soil		1.6	0 (<dl)	0.5	0.1	0.2	0.9				
Vegetation													
		Optimum limits		15-100	0.1-0.5	10.0-40.0	4.0-20.0	na	na	na	na	na	na
28	EPF	Vegetation	1	2.46	0.003	0.222	0.376	0.039	0.224	0.001	0.004		
29	Lagoons	Vegetation	6	1.97	0.006	0.229	0.119	0.204	0.286				
30	Site Camp	Vegetation	3.5	1.06	0.008	0.19	0.138	0.055	0.025				
31	NEF	Vegetation		2.28	0 (<dl)	0.264	0.145	0.109	0.3				
32	X-2 Camp	Vegetation	5.2	2.31	0.01	0.155	0.098	0.008	0.15				
33	L. Side Estate	Vegetation	4.6	1.18	0 (<dl)	0.343	0.207	0.043	0.033				
34	L. View Estate	Vegetation	5.3	1.94	0.013	0.15	0.117	0.003	0.033				
35	L. Naivasha	Vegetation	8.7	2.9	0 (<dl)	0.25	0.05	0 (<dl)	0.65				
36	R. E. Kedong	Vegetation	8.5	2.9	0 (<dl)	0.3	0.2	0 (<dl)	0.7				
37	G.K. Prison	Vegetation	5	2.28	0.02	0.175	0.15	0.03	0.25	0.001	0 (<dl)	0 (<dl)	
38	ODC	Vegetation		7.1	0 (<dl)	0.1	0.2	0.4	0.1				
39	OWF	Vegetation		3.97	0 (<dl)	0.5	0.3	0 (<dl)	0.2				

NOTE:

EPF: East production field

Ptw: Potable treated water

Prw: Potable raw water

Blanks: Not determined

0 (<dl) : Below detection limit

NEF: North east field

OWF: Olkaria west field

ODC: Oserian development company

na: Not available

sp: Seal pit

TABLE 2: Concentration of trace elements in the Olkaria geothermal field for 2nd quarter / June, 1997.

No.	Location	Nature	Zn	Cd	Pb	Cu	Li	Ba	As	Hg	F	B
Water												
Optimum limits			5	0.01	0.05	1	0.25	1	0.05 (0.002)	0.005	1.5	1
1	Lagoon-01	Water (vaste)	0.04	0 (<dl)	0 (<dl)	0 (<dl)	0.1	0 (<dl)			5.4	1.3
2	OW-10 (EPF)	Water (well)	0 (<dl)	0 (<dl)	0.1	0 (<dl)	1.28	0 (<dl)			9.4	5.1
3	X-2 Camp	Water (ptw)	0.03	0 (<dl)	0 (<dl)	0 (<dl)	0 (<dl)	0 (<dl)			9.2	0.11
4	L. Side Estate	Water (ptw)	0.16	0 (<dl)	0 (<dl)	0 (<dl)	0 (<dl)	0 (<dl)			9.3	0.02
5	L. Side Estate	Water (prw)	0	0 (<dl)	0 (<dl)	0 (<dl)	0 (<dl)	0 (<dl)			1	
6	L. View Estate	Water (ptw)	0.24	0 (<dl)	0 (<dl)	0 (<dl)	0 (<dl)	0 (<dl)			9	0.11
7	Kinja Nursery	Water (prw)	0.06	0 (<dl)	0 (<dl)	0 (<dl)	0.09	0 (<dl)			3.8	0.14
Soil												
Optimum limits			5.0 (300)	0.1-1	10.0-40.0	1.0-20.0 (100)	na	na	1	1		5.0-30.0
8	Lagoon-01	Soil	3.9	0.02	0.5	0.18	0.24	2.1				
9	OW-10 (EPF)	Soil	2.15	0.01	0.4	0.08	0.19	0.6				
10	X-2 Camp	Soil	13.5	0.05	1.3	1.38	0.17	5.1				
11	Kinja Nursery	Soil	8.1	0.02	0.3	0.26	0.23	5.1				
12	L. Side Estate	Soil	2.64	0.02	0.4	0.17	0.12	2.3				
13	L. View Estate	Soil	4.7	0.03	0.6	0.12	0.17	2.6				
Vegetation												
Optimum limits			15-100	0.1-0.5	10.0-40.0	4.0-20.0	na	na	na	na	na	na
14	Lagoon-01	Vegetation	1.74	0.03	0.2	0.35	0.26	0.3				
15	OW-10 (EPF)	Vegetation	1.85	0.02	0.1	0.21	0.13	0.5				
16	X-2 Camp	Vegetation	1.51	0.02	0.2	0.14	0.03	0.4				
18	L. Side Estate	Vegetation	0.89	0 (<dl)	0.1	0.05	0.01	0.2				
17	L. View Estate	Vegetation	1.42	0.02	0.1	0.09	0 (<dl)	0.2				
19	Kinja Nursery	Vegetation	1.04	0.02	0.2	0.08	0.08	1.1				

TABLE 3: Concentration of trace elements in the Olkaria geothermal field for 3rd quarter / September, 1997.

No.	Location	Nature	Zn	Cd	Pb	Cu	Li	Ba	As	Hg	F	B
Water												
Optimum limits			5	0.01	0.05	1	0.25	1	0.05 (0.002)	0.005	1.5	1
1	OW-16 (EPF)	Water (well)	0 (<dl)	0 (<dl)	0 (<dl)	0 (<dl)	0.5	0 (<dl)				
2	X-2 Camp	Water (prw)	0 (<dl)	0 (<dl)	0 (<dl)	0 (<dl)	0 (<dl)	0 (<dl)				
3	OW-714 (NEF)	Water (well)	0 (<dl)	0 (<dl)	0 (<dl)	0 (<dl)	1	0 (<dl)				
4	L. Naivasha (Oserian)	Water (prw)	0 (<dl)	0 (<dl)	0 (<dl)	0 (<dl)	0 (<dl)	0 (<dl)				
5	L. Naivasha (KPC)	Water (prw)	0 (<dl)	0 (<dl)	0 (<dl)	0 (<dl)	0 (<dl)	0 (<dl)				
6	L. Naivasha (Karagita)	Water (prw)	0 (<dl)	0 (<dl)	0 (<dl)	0 (<dl)	0 (<dl)	0 (<dl)				
Soil												
Optimum limits			5.0 (300)	0.1-1	10.0-40.0	1.0-20.0 (100)	na	na	1	1		5.0-30.0
7	OW-16 (EPF)	Soil	4.2	0.1	1.8	0.5	0.4	1.7				
8	X-2 Camp	Soil	3.5	0 (<dl)	0.5	0.2	0.1	0.5				
9	OW-714 (NEF)	Soil	2	0 (<dl)	0.4	0 (<dl)	0.1	0.2				
10	L. Naivasha (Oserian)	Soil	2.4	0 (<dl)	0.5	0.2	0.1	1.2				
Vegetation												
Optimum limits			15-100	0.1-0.5	10.0-40.0	4.0-20.0	na	na	na	na	na	na
11	OW-16 (EPF)	Vegetation (Grass)	5.6	0 (<dl)	0.1	0.1	0 (<dl)	0 (<dl)				
12	X-2 Camp	Vegetation (Yams)	5.6	0 (<dl)	0.3	0.1	0 (<dl)	0 (<dl)				
13	X-2 Camp	Vegetation (Kale)	1.3	0 (<dl)	0.2	0 (<dl)	0.4	0 (<dl)				
14	X-2 Camp	Vegetation (Grass)	1.6	0 (<dl)	0.2	0.1	0 (<dl)	0.2				
15	OW-714 (NEF)	Vegetation (Grass)	1.425	0 (<dl)	0.125	0.1	0 (<dl)	0.025				
16	OW-714 (NEF)	Vegetation (Oleleshwa)	2.2	0 (<dl)	0.1	0.4	0.1	0 (<dl)				
17	OW-714, 200m UW (NEF)	Vegetation (Oleleshwa)	1.9	0 (<dl)	0.1	0.3	0.1	0 (<dl)				
18	OW-714, 200m DW (NEF)	Vegetation (Grass)	0.7	0 (<dl)	0.1	0.1	0.5	0.1				
19	OW-714, 200m DW (NEF)	Vegetation (Oleleshwa)	1.7	0 (<dl)	0.2	0.4	0.7	0 (<dl)				
20	L. Naivasha (Oserian)	Vegetation (Papyrus)	0.8	0 (<dl)	0.1	0 (<dl)	0 (<dl)	0 (<dl)				
21	L. Naivasha (KPC)	Vegetation (Papyrus)	0.8	0 (<dl)	0.1	0.2	0 (<dl)	0.4				
22	L. Naivasha (Karagita)	Vegetation (Papyrus)	0 (<dl)	0 (<dl)	0 (<dl)	0 (<dl)	0 (<dl)	0 (<dl)				

TABLE 4: Average concentration of trace elements in the Olkaria geothermal field for 1st quarter / March, 1998.

No.	Location	Nature	pH	TEMP (°C)	TDS	COND.	Zn	Cd	Pb	Cu	Li	Ba	As	Hg	F	B
Water																
Optimum limits			6.5-8.5				5	0.01	0.05	1	0.25	1	0.05 (0.002)	0.005	1.5	1
1	Lagoon-01	Water (waste)					0.17	0 (<dl)	0 (<dl)	0.007	0.2	0 (<dl)				
2	Lagoon-02	Water (waste)					0.92	0 (<dl)	0 (<dl)	0 (<dl)	0.4	0 (<dl)				
3	Lagoon-03	Water (waste)					0.52	0 (<dl)	0.1	0.01	0.35	0.1				
4	Power Plant-sp	Water (waste)	3.86	39	190	123										
5	OW-02 (EPF)	Water (well)	8.26	83	2670	1826	0.075	0 (<dl)	0.1	0.015	0.75	0 (<dl)				
6	OW-06 (EPF)	Water (well)	8.33	44	3980	3196	0.52	0 (<dl)	0.1	0.035	0	0.2				
7	OW-21 (EPF)	Water (well)	8.51	82	130		2.99	0 (<dl)	0.6	0.13	0.1	3				
8	OW-22 (EPF)	Water (well)	9.11		1860		0.005	0 (<dl)	0.1	0 (<dl)	0.45	0 (<dl)				
9	OW-25 (EPF)	Water (well)	8.4		3020	1972	0.03	0 (<dl)	0.1	0.01	0.9	0 (<dl)				
Soil																
Optimum limits							5.0 (300)	0.1-1	10.0-40.0	1.0-20.0 (100)	na	na	1	1		5.0-30.0
10	Lagoon-01	Soil					4.71	0 (<dl)	0.8	0.3	0.15	2.05				
11	Lagoon-02	Soil					2.38	0 (<dl)	0.55	0.115	0.1	0.95				
12	Lagoon-03	Soil					3.325	0 (<dl)	0.65	0.18	0.15	2.3				
13	Power Plant-sp	Soil					3.38	0 (<dl)	0.6	1.63	0.1	1.4				
14	OW-02 (EPF)	Soil					4.25	0 (<dl)	0.8	0.15	0.1	1				
15	OW-06 (EPF)	Soil					2.245	0 (<dl)	0.45	0.09	0.1	0.7				
16	OW-21 (EPF)	Soil					4.82	0 (<dl)	3.05	0.27	0.1	3.25				
17	OW-22 (EPF)	Soil					3.09	0 (<dl)	0.4	0.09	0.1	0.8				
18	OW-25 (EPF)	Soil					7.84	0 (<dl)	1	0.205	0.1	1.55				
Vegetation																
Optimum limits							15-100	0.1-0.5	10.0-40.0	4.0-20.0	na	na	na	na	na	na
19	Lagoon-01	Vegetation (Grass)					2.21	0 (<dl)	0.2	0.25	0.1	1.2				
20	Lagoon-02	Vegetation (Grass)					2.535	0 (<dl)	0.3	0.54	0.05	0.55				
21	Lagoon-03	Vegetation (Grass)					1.78	0 (<dl)	0.2	0.24	0.1	0.3				
22	Power Plant-sp	Vegetation (Grass)					2.26	0 (<dl)	0.2	0.51	0 (<dl)	0.5				
23	OW-02 (EPF)	Vegetation (Grass)					10.325	0 (<dl)	1.25	0.305	0.25	0.4				
24	OW-06 (EPF)	Vegetation (Grass)					2.02	0 (<dl)	0.2	0.28	0 (<dl)	0 (<dl)				
25	OW-21 (EPF)	Vegetation (Grass)					1.76	0 (<dl)	0.25	0.305	0 (<dl)	0.3				
26	OW-22 (EPF)	Vegetation (Grass)					3.665	0 (<dl)	0.2	0.345	0.1	0.6				
27	OW-25 (EPF)	Vegetation (Grass)					2.26	0 (<dl)	0.1	0.21	0.1	0.9				