American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN : 2320-0936
Volume-5, Issue-4, pp-152-157
www.ajer.org
Research Paper Open Access

Overview of Land Contamination Management and Site Remediation

[1]Sani S. Malami [2]Muhammad Abubakar and [3]Rintong Isaac Babatunde
[1&2]*Department of Mechanical Engineering, Kaduna polytechnic, Kaduna.*
[3]*Department of Civil Engineering, Kaduna polytechnic, Kaduna. Nigeria.*

ABSTRACT: *Land contamination has caused health problems to land owners, occupiers and a threat to the ecosystem. This contamination may be on the increase as a result of the acceleration of urbanization and rapid development of economy. This paper has discussed the causes of land contamination and it effects on the environment and site remediation which covers soil remediation and environmental water remediation.*
Keywords: *Contamination, Environment, Remediation, Groundwater, Sustainable.*

I. INTRODUCTION

Contaminated land is a liability to the owners, occupiers, financiers and insurers. Apart from health problems and threats to the ecosystem, it causes rental and capital value reduction, and legal and financial liabilities. To safeguard the stakeholders' interest, it is required to properly manage both contaminated and potentially contaminated property. The conventional property management methods are applicable subject to modification to include identification of contamination on the land, assessment of the environmental risk and preparation of a dedicated management program(Nelson Chan (1999))

Soil contamination by organic or inorganic pollutants is caused by a number of industries such as chemical, pharmaceuticals, plastics, automobile, nuclear industries, biomedical wastes, mining industries, municipal solid waste. At times it becomes essential to decontaminate soil. Broadly the soil decontamination is done in two ways: (a) pump and treat in which the pollutant is pumped out using external energy source, treated using methods such as incineration, radiation, oxidation etc (b) removal of contaminated soil, treat it and then returning back to its original place. This module is meant to briefly introduce various soil/ water decontamination processes. The scientific basis and the reactions involved in these processes are acid-base chemistry, solubility-precipitation, ion exchange, redox, complexation, sorption.

There are many causes of land contamination. Basically land may become contaminated due to the presence of natural or artificial contaminants. Natural minerals like asbestos, uranium, etc. may contaminate land if they are disturbed or exposed. Land contamination due to undisturbed natural minerals is rare. More often than not, land contamination is due to human activities such as industrial productions, farming, and accidents, etc. The contaminants are generally in the form of products, by-products and wastes.
In recent years, with the development of the global economy, both type and content of heavy metals in the soil caused by human activities have gradually increased, resulting in the deterioration of the environment (Han et al., 2002; Sayyed and Sayadi, 2011; Jean-Philippe et al., 2012; Raju et al., 2013; Prajapati and Meravi, 2014; Sayadi and Rezaei, 2014; Zojaji et al., 2014). Heavy metals are highly hazardous to the environment and organisms. It can be enriched through the food chain. Once the soil suffers from heavy metal contamination, it is difficult to be remediated. In the past, soil contamination was not considered as important as air and water pollution, because soil contamination was often with wide range and was more difficult to be controlled and governed than air and water pollution. However, in recent years the soil contamination in developed countries becomes to be serious. It is thus paid more and more attention and became a hot topic of environmental protection worldwide. To understand the current situation and the impact of heavy metal contamination of soils in the world, in present study we will compare and analyze the contamination data of various cities/countries, and explore background, impact and remediation methods of heavy metal contamination of soils.

Heavy metal pollution refers to cases where the quantities of these elements in soils are higher than the maximum allowable concentrations, and this is potentially harmful to biological life at such locations. As noted by Gazso (2001), heavy metals come from a variety of sources but human economic activities such as coal and metal ore mining, chemical manufacturing, petroleum mining and refining, electric power generation, melting and metal refining, metal plating and to some extent domestic sewage are principally responsible. Some of the heavy metals such as Cu, Ni and Zn are essential to plants and animals in very low concentrations by serving as components of enzymes, structural proteins, pigments and also helping to maintain the ionic balance of cells (Kosolapov et al., 2004). These and other trace elements are important for proper functioning of biological systems and their deficiency or excess could lead to a number of disorders. Food chain contamination by heavy metals has become a burning issue in recent years because of their potential accumulation in biosystems through contaminated water, soil and air. As observed by Begun et al. (2009), large quantities of pollutants have continuously been introduced into ecosystems as a consequence of urbanization and industrial processes. Metals are persistent pollutants that can be biomagnified in the food chains, becoming increasingly dangerous to human beings and wildlife. Therefore, assessing the concentrations of pollutants in different components of the ecosystem has become an important task in preventing risk to natural life and public health. Heavy metals enter into the environment mainly via three routes namely: (i) deposition of atmospheric particulate, (ii) disposal of metal enriched sewage sludges and sewage effluents and (iii) by-products from metal mining process. Soil is one of the repositories for anthropogenic wastes. Biochemical processes can mobilize them to pollute water supplies and impact food chains. Heavy metals such as Cu, Cr, Cd, Ni, and Pb are potential soil and water pollutants. Globally, the problem of environmental pollution due to heavy metals has begun to cause concern in most large cities since this may lead to geoaccumulation, bioaccumulation and biomagnifications in ecosystems.

Heavy metal contaminants in the environment are eventually deposited in soils in some form of a low solubility compound, such as pyrite (Huerta-Diaz and Morse, 1992) or sorbed on surface-reactive phases, such as Fe and Mn oxides (Cooper et al., 2005; Hamilton- Taylor et al., 2005). Lead (Pb) is the most common environmental contaminant found in soils. Unlike other metals, Pb has no biological role, and is potentially toxic to microorganisms (Sobolev and Begonia, 2008). Its excessive accumulation in living organisms is always detrimental. Furthermore, Pb exposure can cause seizures, mental retardation, and behavioral disorders in human beings. Heavy metal exposure to human beings occurs through three primary routes namely inhalation, ingestion and skin absorption. All these occur in myriads of places including auto-mechanic workshops. Generally, toxic metals cause enzyme inactivation, damage cells by acting as antimetabolites or form precipitates or chelates with essential metabolites. According to USDA (2000), acute (immediate) poisoning from heavy metals is rare through ingestion or dermal contact, but it is possible. Chronic problems associated with long-term heavy metal exposures are mental lapse (lead); toxicological effects on kidney, liver and gastrointestinal tract (cadmium); skin poisoning and harmful effects on kidneys and the central nervous system (arsenic). There is a link between long term exposure to copper and decline of intelligence in young adolescents (Lenntech,.)

Risk assessment of contaminated site

Risk assessment or hazard assessment is required to decide the extent of contaminant remediation required for a particular site. The factors influencing risk assessment are:

Toxicity

A material is deemed toxic when it produces detrimental effects on biological tissues or associated process when organisms are exposed to concentration above some prescribed level. Acute toxicity is the effect that occurs immediately after exposure where as chronic toxicity deals with long term effects. It is expressed as mass unit of toxicant dose per unit mass of receiving organism. It must be noted that concentration is an important factor while deciding toxicity. Only when a contaminant crosses a particular concentration, it becomes toxic. If the concentration is within the prescribed limit then no remediation need to be performed. Only those site which have toxic level of contaminant concentration needs remediation. For example, toxic contamination level leading to cancer becomes the basis for some of the site clean-up programs.

Reactivity

It is the tendency to interact chemically with other substances. These interactions become hazardous when it results in explosive reaction with water and/or other substances and generate toxic gases.

Corrosivity

Corrosive contaminants degrade materials such as cells and tissues and remove matter. It is defined as the ability of contaminant to deteriorate the biological matter. Strong acids, bases, oxidants, dehydrating agents are corrosive. $pH < 2$ or $pH > 12.5$ is considered as highly corrosive. Substances that corrode steel at a rate of 6.35 mm/year is also considered hazardous.

Ignitability

It is the ease with which substance can burn. The temperature at which the mixture of chemicals, vapour and air ignite is called the flash point of chemical substances. Contaminants are classified as hazardous if it is easily ingnitable or its flash point is low.

Based on the above four factors the risk associated with a particular site is determined by specifying maximum acceptable risk using risk estimation equations (Reddi and Inyang 2000). Risk assessment provides a numerical quantification of the probability of harm from hazardous or toxic contamination. Risk management uses this input of risk assessment in deciding how much regulation and corrective measure need to be taken. The corrective action is mostly the practice of remediation of the contaminated site. The maximum possible concentration that could lead to the maximum acceptable risk is back

calculated. If the level of concentration at a particular site is greater than the maximum possible concentration, then it requires remediation. This approach would clearly indicate the extent of remediation required for the contaminated site. Appropriate remediation scheme is then selected to bring the concentration level much less than the maximum possible concentration. Since risk assessment and risk management is a very broad topic, it is difficult to discuss the mathematical formulation in this course. Interested readers are requested to go through additional literature (USEPA 1989; Asante-Duah 1996; Mohamed and Anita 1998) If the level of concentration at a particular site is greater than the maximum possible concentration, then it requires remediation. This approach would clearly indicate the extent of remediation required for the contaminated site. Appropriate remediation scheme is then selected to bring the concentration level much less than the maximum possible concentration. (USEPA 1989; Asante-Duah 1996; Mohamed and Antia 1998).

II. SITE REMEDIATION TECHNIQUES

Remediation method for contaminated water are physical biological and chemical means but covers soil remediation and Environmental water remediation. Environmental water are surface water and ground water.

1.1 Remediation of surface and ground water

Groundwater is the main source of drinking water as well as agricultural and industrial usage. Unfortunately, groundwater quality has been degraded due to improper waste disposal practices and accidental spillage of hazardous chemicals. Therefore, it is critical that the groundwater contamination be prevented and the contaminated groundwater at numerous sites worldwide be remediated in order to protect public health and the environment.

Biodegradation is the disappearance of environmentally undesirable properties of a substance. Biodegradation is different from biotransformation, the conversion of an organic compound into a large molecular structure or loss of a characteristic property with no decrease in molecular complexity. In biotransformation the toxicity, form, and mobility of the original compound is altered. This is true of biodegradation, too. Biodegradation is caused by microorganisms. These are bacteria, fungi, and microfauna (e.g. protozoans, some worms, and some insects). Microorganisms degrade substances using specific and non-specific processes.

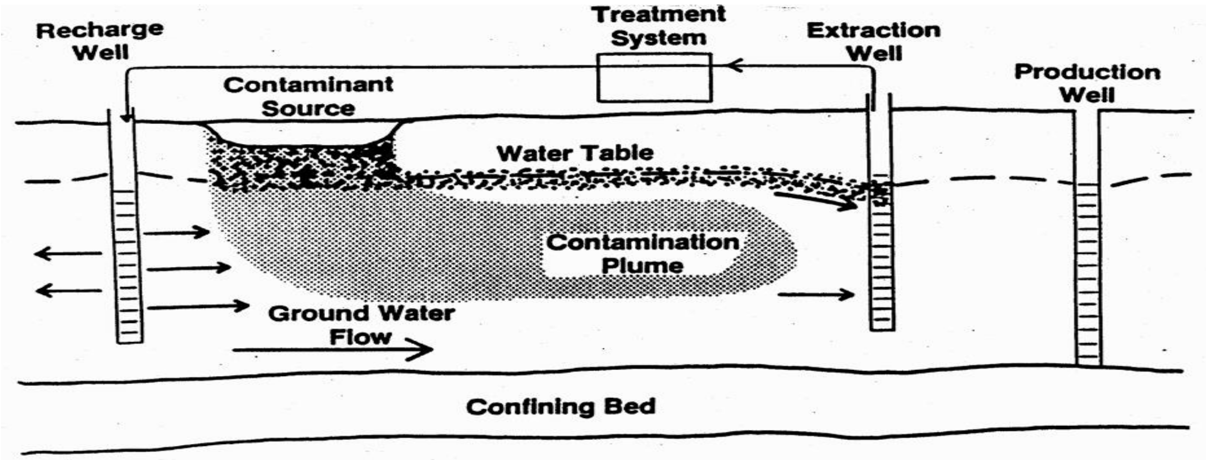
Specific processes refer to a microbe targeting a single site of a molecule as the pivotal action in biodegradation. Non-specific processes are those with a chain of microbial events in the biodegradation of waste. Degradation pathways are determined quite often by environmental conditions such as pH, molecular oxygen and nutrient conditions. For example, petroleum products are best degraded in the presence of oxygen, aerobic conditions. Highly halogenated compounds require anaerobic conditions to remove the halogens. The biodegradation of a particular waste may require a series of different environmental conditions for a variety of microorganisms to cause a cascade of reactions. The chlorinated compounds, for example, first require reductive dechlorination in anaerobic conditions followed by breakdown of organics in aerobic conditions. Bacteria such as prokaryotes are unicellular organisms containing circular genetic material not enclosed by a nuclear membrane. They are often distinguished by their sources of energy and their electron acceptors for respiration.

Bacteria that use light as a source of energy are called phototrophs. Some bacteria oxidize organic matter and are called heterotrophs. Others oxidize inorganic compounds; these are the lithotrophs or chemoautotrophic bacteria. Bacteria that use oxygen to accept the electrons generated in respiration are aerobic. Inorganic acceptors are used by anaerobic bacteria.Others are iron reducers, sulfate reducers, and carbon dioxide reducers. Bioremediation of surface and groundwater will remain expensive for some time [Nelson Chan (1999)]. The heating of water prior to biological treatment has been a prerequisite and dramatically increases the treatment expenses [Asante-Duah, D. K. (1996]. Recent studies indicate that considerable potential exists for biological systems, but the many factors that influence degradation and the rate at which it occurs are largely unknown [Ghosh M, Singh SP (2005).]. There has been little experience with in-situ biological treatment of contaminated groundwater, and there have been virtually no field applications [Ghosh M, Singh SP (2005).]. Ex-situ treatment is typically more controllable and predictable and technically less complex than in-situ treatment.

1.2 Remediation Techniques for ground water

The most common physical and chemical remediation technologies are pump and treat, in-situ air sparging, in-situ flushing, and permeable reactive barriers.

Pump and treat: With pump and treat free-phase contaminants and/or contaminated groundwater are pumped directly out of the surface. Treatment occurs above ground, and the cleaned groundwater is either discharged into sewer systems or re-injected into the subsurface (Cohen et al., 1997).



Air sparing: During the implementation of air sparging, a gas, usually air, is injected into the saturated soil zone below the lowest known level of contamination. Due to the effect of buoyancy, the injected air will rise towards the surface. As the air comes into contact with the contamination, it will, through a variety of mechanisms, strip the contaminant away or assist in in-situ degradation. Eventually, the contaminant laden air encounters the vadose zone, where it is often collected using a soil vapor extraction system and treated on-site (Reddy et al., 1995; Reddy and Adams, 2001).

This technology has been very popular because it causes minimal site disruption and reduces worker exposure to contaminants, it does not require removal, storage, or discharge consideration for groundwater, the equipment needed is simple and easy to install and operate, it requires short treatment time (1–3 years), and the overall cost is significantly lower than the conventional remediation methods such as pump and treat. However, there are several limitations of this technology.

Contamination in low permeability and stratified soils poses a significant technical challenge to air sparging remediation efforts. Confined aquifers cannot be treated by this remediation technique. Air flow dynamics and contaminant removal or Soil flushing involves pumping flushing solution into groundwater via injection wells. The solution then flows down gradient through the region of contamination where it desorbs, solubilizes, and/or flushes the contaminants from the soil and/or groundwater. After the contaminants have been solubilized, the solution is pumped out via extraction wells located further down gradient. At the surface, the contaminated solution is treated using typical wastewater treatment methods, and then recycled by pumping it back to the injection wells (USEPA, 1991; Roote, 1997). Permeable reactive barriers (PRBs) offer a passive approach for groundwater remediation. In general, a permeable wall containing an appropriate reactive material is placed across the path of a contaminant plume. As contaminated water passes through the wall, the contaminants are either removed or degraded.

1.3 Remediation Techniques for surface water

The methods adopted for surface water remediation are through aquatic plants aquatic animals and the use of microorganisms.

Aquatic plants: The plants with strong absorption for pollutants and good tolerance could be planted in the polluted water. Accordingly these plants can mitigate or fix water pollutants through adsorption, absorption, accumulation and degradation for water purification(Gagnon et al., 2012; Wang et al, 2012).However, plants vary considerably in their tolerance of pollutants and in the amount of that they can take up from soils and water. Some of these accumulating plant species reveal the mineral composition of those substrates, for example, in the soil, sediment and water. This ability can be used in contamination bio-indication or, if the biomass and bio-productivity are high, in phytoremediation (Favas et al., 2012).

Aquatic animals: In comparison to physical and chemical remediation methods, biological treatment for phytoplankton control in large water body, such as lakes and reservoirs are effective (Ma et al., 2010, 2012b). Plus, it is well documented that aquatic animals such as clam, snail or other filter-feeding shellfish had prominent effect on nutrients removal in eutrophic water body (Li et al., 2010; Wang et al, 2012). The biological treatment of stocking filter-feeding silver carp in eutrophic water body has been widely applied to control excessive phytoplankton and improve water quality in the world (Xiao et al., 2010; Ma et al., 2010, 2012a)
Generally, silver crap (Hypophthalmichthys molitrix) have a long lifespan (~6-10 years, or even 20 years) in natural water bodies (Ma et al., 2012a). Silver carp is commonly stocked in reservoirs in developing countries and was intensively stocked in newly constructed reservoirs in China in the 1970s. It is an omnivorous filter-feeder that can filter particles > 10 μm, including zooplankton and phytoplankton (Xiao et al., 2010).

Microorganism: In this technology microorganisms are used to decompose, transform, absorb the pollutant in the water. Results to date generally confirm the existence of the appropriate microbial functional groups, e.g. nitrifiers, denitrifiers, SRB, SOB etc., responsible for removal of specific pollutants the wastewater (Faulwetter et al., 2009; Wang et al, 2012).

1.4 REMEDIATION OF SOILS

Biological remediation: Biodegradation generally refers to the breakdown of organic compounds by living organisms eventually resulting in the formation of carbon dioxide and water or methane. Inorganic compounds are not biodegraded, but they can be biotransformed, that is, transformed into compounds having more or less mobility or toxicity than their original form. In many cases, the biodegradation processes involve a particular microorganism that attacks a specific molecular site. Complete and rapid biodegradation of many contaminants may require, not only specific environmental conditions, but also changing conditions to satisfy the needs of the microbe (Tsang et al.) have investigated the mobility of several different metals in soil and the influence of the biodegradation process on that mobility. They have shown that active microorganisms influence the ability of soil to retain or release metals and that cysteine is an effective agent for the release of some metals from soil.
Chemical remediation: In-situ immobilization can be carried out by introducing treatment chemicals into the ground by various means. If soluble chemicals are used, they can be applied by saturating the soil with the chemical solution. This fluid application may be carried out at a high rate by surface flooding the site or more gradually by spraying and allowing the solution to drain freely into the soil. The variation in application rate will affect the period of soil exposure to the treatment material, the degree of void filling accomplished, and the amount of air present in the soil during the treatment period. A complementary confinement or pumping system may be appropriate if the soluble treatment chemical has undesirable environmental effects or is worth recycling due to high chemical costs [Markers. Int. J. Environ].
Insoluble chemicals can be introduced into the ground by spreading, filling, forced injection, suspension transport, or by placing it in a low permeability encapsulation barrier. Spreading may suffice as a means of treating metals if the soil has a high moisture content and the metal contaminants lie close to the surface. This may be most applicable to soils with high organic content.
Oxidation, in waste remediation, refers to the movement of a contaminant to a more oxidized or more environmentally benign state. Oxidation technologies form part of the many treatment alternatives that have the capability to reduce or eliminate both the volume and toxicity of contaminants. Three technologies are summarized that utilize oxidation as a treatment method:
(1) chlorine dioxide and hydrogen peroxide additives,
(2) photolysis,
(3) reductive dechlorination.

Chlorine dioxide and hydrogen peroxide are easy to incorporate into various environmental media under treatment, including water, waste water, leachate, air, and soil. Chlorine dioxide and hydrogen peroxide are frequently used as disinfectants, bleaching, and oxidizing agents. They can oxidize hazardous materials that are either organic or inorganic compounds. Sometimes when these oxidizing agents cannot completely degrade the contaminants, they can transform the contaminants into constituents that are amenable to other forms of degradation, such as biological processes.

Hydrogen peroxide is utilized in environmental applications as a chemical oxidizing agent and as a source of oxygen. It effectively and easily oxidizes organic and ring compounds. It also is
economical, easily available at low cost in a form ready for application. While it leaves no harmful by-products, slow and incomplete reactions with some species, such as saturated alkanes, have been documented. Because it is an oxygen source, hydrogen peroxide can be used in the subsurface for bioremediation applications.

Many organic compounds absorb light energy at visible or ultraviolet wavelengths. This energy
promotes the decomposition of the chemical. Ultraviolet radiation is sufficient to cleave many types of covalent bonds. It has been shown to degrade PCBs, dioxins, PAHs, and several aromatic constituents of gasoline, including benzene, toluene, ethylbenzene, and xylene. This technique is advantageous in that organic waste is destroyed and the generated residuals are minimal. Although the application of photolytic treatments outside the lab has been limited, the results from the few pilot studies conducted are promising. Liquid, gaseous, and solid media are suitable to such treatment. For a technique to be effective, a high proportion of the surface area of the medium must be exposed to light. Ultraviolet light is sometimes used to intensify the oxidation process in the presence of the principal oxidizing chemicals, such as ozone or hydrogen peroxide.

Reductive dechlorination has been used on soil contaminated with PCBs and other organic chemicals. This process mixes contaminated liquids, soils, and sludges with an alkali-metal hydroxide reagent in a treatment reactor. Reductive dechlorination, like oxidation, modifies the molecular structure of the contaminant such that the contaminant is transformed to a more benign substance. The treatment removes chlorine atoms from hydrogen-carbon molecules. These molecules are then amenable to destruction by means of biological treatment and other technologies.

III. CONCLUSSION

Environmental protection is one of the pillars of sustainable development, land contamination and site remediation are inseparable if we must achieve the sustainable development goal as proposed through the agenda 21.This paper have suggested the application of in-situ method of site remediation as a better and economical means of decontamination.

REFERENCES

[1] Nelson Chan (1999) Faculty of Management University of Western Sydney, Hawkesbury

[2] Huerta-Diaz MD, Morse JW (1992). Pyritization of Trace Metals in mAnoxic Marine Sediments. Geochim. Cosmochim. Acta., 56: 2681- 2702.

[3] Kosolapov DB, Kuschk P, Vainshtein MB, Vatsourina AV, Wiebner A, Kasterner M, Miler RA (2004). Microbial Processes of Heavy Metal Removal from Carbon Deficient effluents in constructed wetlands. Eng. Life. Sci., 4(5): 403–411.

[4] Sobolev D, Begonia MFT (2008). Effects of Heavy Metal Contamination upon Soil Microbes: Lead-induced Changes in General and Denitrifying Microbial Communities as Evidenced by Molecular

[5] Markers. Int. J. Environ. Res. Public Health, 5(5): 451

[6] Begum A, Ramaiah M, Harikrishna, Khan I, Veena K (2009). Analysis of Heavy Metals Concentration in Soil and Litchens from Various Localities of Hosur Road, Bangalore, India. E-J. Chem., 6(1): 13-22. http://www.e-journals.net

[7] Gazso LG (2001). The Key Microbial Processes in the Removal of Toxic Metals and Radionuclides from the Environment. A review. Cent. Eur. J. Occup. Environ. Med., 7(3): 178–185.

[8] Ghosh M, Singh SP (2005). Comparative Uptake and Phytoextraction Study of Soil Induced Chromium by Accumulator and High Biomass weed Species. Appl. Ecol. Environ. Res., 3(2): 67-79. http://www.ecology.kee.hu.

[9] Gillette B (2008). Nickel named 'Allergen of the Year'. ACDS adds to list of substances warranting more attention. Dermat. Times, 4: 15-16.

[10] Gimmler H, Carandang J, Boots A, Reisberg E, Woitke M (2002). Heavy Meta Content and Distribution within a Woody Plant during and after Seven Years continuous Growth on Municipal Solid Waste (MSW) Bottom slag Rich in Heavy Metals. J. Appl. Bot., 76: 203–217.

[11] Goyer RA, Clarkson TW (2001). Toxic Effects of Metals. In, Casarett and Doullis Toxicology: The Basic Science of Poisons, Sixth Edition (C.D. Klaassen, ed.) Mc-Graw-Hill, New York, pp. 811-867.

[12] Hamilton-Taylor J, Smith EJ, Davison W, Sugiyama M (2005). Resolving and Modeling the Effects of Fe and Mn Redox Cycling o

[13] Australian and New Zealand Environment and Conservation Council, National Health and Medical Research Council(ANZECC & NHMRC), "Australian And New Zealand Guidelines For The Assessment And Management Of Contaminated Sites", 1992.

[14] Australian Institute of Valuers and Land Economists (AIVLE), "Contaminated Land Practice Standard", 1994, pp. 15-17.

[15] Australian National Audit Office (ANAO), "Environmental Management of Commonwealth Land Site Contamination and Pollution Prevention", 1996, pp. 83-96.

[16] Department of Environment, Queensland (DoE, Qld), 1998, "Draft Guidelines for the Assessment & Management of Contaminated Land in Queensland".

[17] Hadley, M., "Environmental audits as a tool for commercial property management", Property Management, Vol. 10, No. 2, 1994, pp. 141 – 149.

[18] Izmir, G., "Clean and Competitive with ISO 14000", *WM&E Sourcebook, Waste Managment &*

[19] Asante-Duah, D. K. (1996) "Management of Contaminated Site Problems", Lewis Publ., CRC Press Inc., Boca Raton, Florida.

[20] Ascenco, C. (2009) "Contaminated site characterization and clean up-two case studies", NASA/c3p- 2009 International workshop on environment and alternative energy: Global Collaboration in Environmental and Alternative Energy Strategies" http://www.wspgroup.com/en/WSP-Group/Sustainability/Case-Studies-3/Land- remediation (Website visited on 7-11-2011)

[21] Asquith, E. A. and Geary, P. (2011) "Comparative bioremediation of petroleum hydrocarbon-contaminated soil by biostimulation, bioaugmentation and surfactant addition", 4th International Contaminated Site Remediation Conference, Clean up 2011, Adelaide, South Australia, pp. 261-262.

[22] Evangelou, V. P. (1998) "Environmental soil and water chemistry: principles and applications", Wiley-Inderscience, New York.

[23] Harbottle, M. J., Al-Tabbaa, A. and Evans, C. W. (2006) "Assessing the true technical/ environmental impacts of contaminated land remediation – a case study of containment, disposal and no action", Land, Contamination and Reclamation, Vol. 14 (1), pp. 85-99.

[24] Ludwig, R. D., Wilkin, R. T. and Su, C. (2011) "Treatment of Cr6 in groundwater using prb systems", 4th International Contaminated Site Remediation Conference, Clean up 2011, Adelaide, South Australia, pp. 7-8. http://www.cleanupconference.com/program.html (website visited on 7-11-2011