Management of Long-Term Environmental Changes Caused By Industrial Pollution

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Abstract

One common source of frustration to policy makers involved in environmental management is that mitigating measures are sometimes followed by a worsening of the unwanted conditions rather than an improvement. This paper attempts to explain the causes and suggest an effective strategy for managing long – term environmental changes so as to avoid situations capable of frustrating policy makers. Attributes of soils and sediments that cause non- linear and time- delayed effects of certain pollutants in the environment are identified as buffering capacity , absorption of chemical materials and oxygen donating capacity. Specific cases where these attributes had affected bioavailability of toxic and ecologically harmful substances in the USA and Central Europe are highlighted. A long term strategic management of the environment which employs a two- dimensional matrix that identifies the source environmental change on the one axis and a small set of 'Critical Environmental Indicators' (CEIs) on the other is advocated. This method adopts the synoptic approach to complex –inter –relationships between economic development and environmental change as well as identifies both the primary and secondary linkages between development activities and environmental transformations. This 'Bottom –up' approach which tackles pollution problems right from their cause is advocated. The need for policy makers to pay more attention to environmental monitoring systems which provide early warning of fundamental ecological change is stressed.

Keywords: *Acidification, Buffering Capacity, Ecosystem, Environmental Management, Pollutants*

Introduction

Disposal of industrial, municipal and domestic wastes into streams, lakes, and river has become the major anthropogenic source of surface water pollution. Industrial effluents contain high volumes of carbon–containing wastes that place a high oxygen demand on receiving waterbodies. Indices of these oxygen demands are Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD). High BOD or COD reduces the redox potential of receiving waters making them anoxic this is because the effluents contain high concentrations of bacterial and viral life which consume the much needed Dissolved Oxygen (DO). Toxic heavy metals and organic chemicals are also generated by industrial activities mostly from chemicals and petrochemical industries. Heavy metals for example are generated from electroplating and metal finishing industries, scrap metal recycling, smelting of metal ores, fossil fuel refining, coal mining, paper pulping etc.

Sediments in freshwater, estuarine and marine ecosystem serve as sink or source for these toxic metals depending on their redox conditions (Stigliani, 1988, Rabalais *et al.*, 2007). Soils and sediments possess three important physico-chemical attributes which are of great environmental significance because of the way they influence bioavailability of toxic and ecologically harmful substances. These attributes are the capacity to buffer acidity, absorb ambient chemical materials and donate oxygen (i.e. to act as oxidizing agent). They have the ability to exhibit a delayed response to acidification until after a few decades of acid deposition. The Adirondack Mountain of the USA is a good example of soil with moderate buffer capacity. The area covered by this mountain serves as a watershed for the Big Moose Lake in New York where acid sensitive species have been disappearing since mid-1950s. This lake is one of the few examples in the world where accurate and extensive information exists on the trends in pH, SO_2 emissions and fish populations. The trends in these parameters for slightly more than two centuries are presented in Fig. 2.

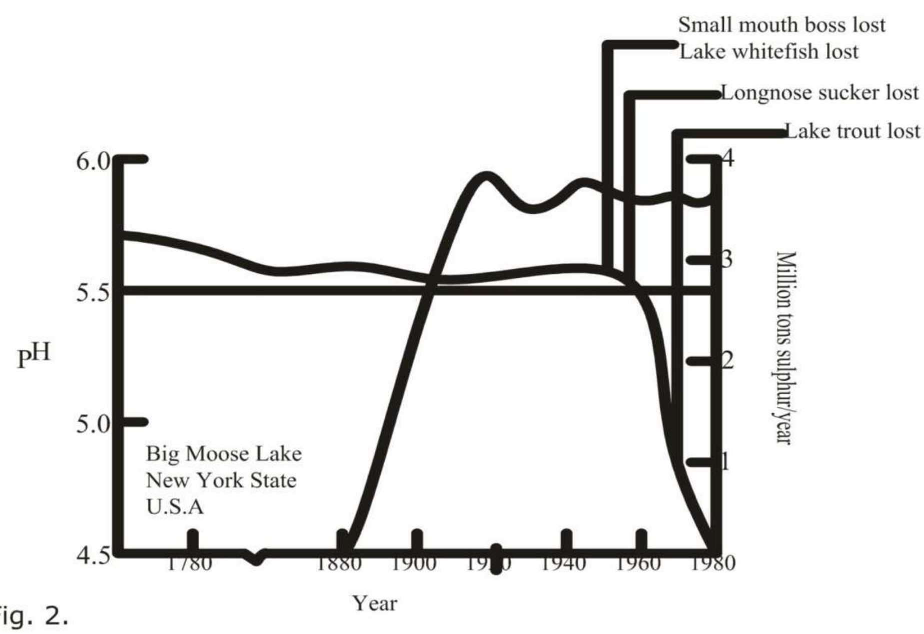

Fig. 2.

Trends in pH emissions of SO2 upwind from the Big Moose Lake and fish extinctions for the period from 1760 to 1980. The pH history was reconstructed by analysis diatom assemblages in the sediment core samples. The history of emissions of SO2 upwind from the lake was estimated from data on fuel consumption and sulphur content in coal consumed.

Source: Stigliani (1988)

This figure reveals that the onset of decline in pH was not synchronised to the onset of SO_2 emissions. The soils of this area buffered acid deposition for about 70 years (1880 to 1950). Even when SO_2 emission reached a peak, the buffering capacity continued for 30 years (1920- 1950). A drastic reduction in pH later occurred within a 30 year period (1950-1980) when SO_2 emissions had more or less stabilized. Although the pH reduction was only by one unit, it was drastic because it corresponded to a factor of 10 increase in acidity. During this period of pH decline, atmospheric deposition must have moved through the buffered depleted soils and percolated into lakes with little or no neutralization. At the onset of this period, acid sensitive fish species started disappearing (see Fig.1).

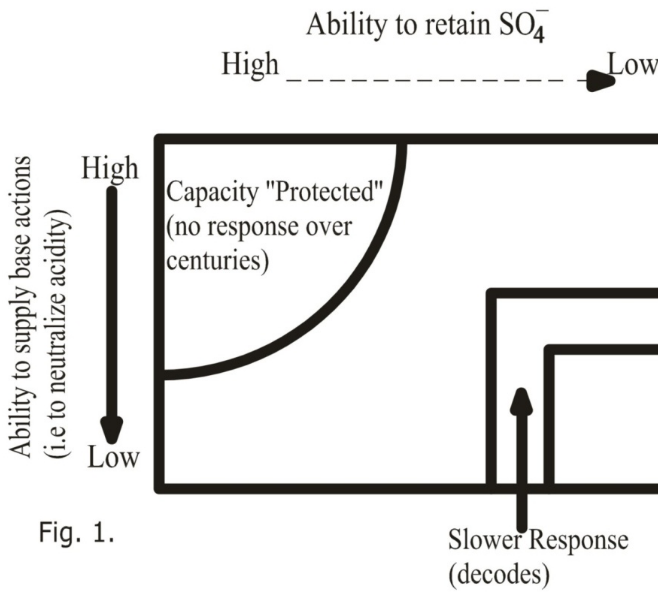

Fig. 1.

A qualitative representation of the effect of two major soil properties- the ability to retain sulphate and the ability to supply base cations – on the rate at which streams and lakes respond to changes in acid deposition.
Source : NRC, 1984

Other areas in literature where ecosystems have been affected by acidification in the US and UK include Catskill Mountain, Appalachian Highland, Little Echo Pond, Chesapeake Bay, Colorado Rocky Bay and many more. Acid rain has been harming the ecosystems of the Catskill Park for as long as the Adirondack. While the Catskill Park is one tenth of the Adirondack and has fewer lakes, the legendary rivers and trout streams have lost much of its vitality. In New England, the hard wood forest of New Hampshire Hubbard brook area has stopped growing. Chesapeake Bay is facing a condition known as hypoxia.

The history of acidification of the Big Moose Lake demonstrates Brooks' hypothesis of benefits and disbenefits from application of technologies. Brook (1986) postulated that industrial societies gain certain socio-economic 'benefit' from broad scale applications of technologies, but such 'benefits' are often accompanied by 'disbenefits' to the environment as a whole. Benefits are usually directly proportional to the scale of application of the technology while disbenefits may vary non-linearly as shown in Fig.3. The marginal benefit in such situations is usually highest at the onset of production before the disbenefits start to manifest. As disbenefit increases, marginal benefit declines gradually. Benefits are typically manifested on 'fast' time scales while disbenefits may become obvious only on relatively 'slow' ones. This is exactly the situation in the history of acidification of the Big Moose Lake where burning of fossil fuels in neighbouring industries provided energy to drive machinery in the manufacture of many useful products for about 70 years before the consequent effects of lake acidification started to manifest.
In Central Europe, soils are generally more resistant to acidification than in the Scandinavia where the buffering capacities of soils are comparable to those of the Adirondack Mountains of the USA. According to Alcano *et al.*, (1987) Sulphur depositions in the last two decades in Central Europe have been so high that about 20% of

the total areas have reached their limits for neutralising acids (i.e. with pH values less than 4). Vulnerability to acidification is a time delayed disbenefit of Sulphur emissions which will continue to spread to Europe unless SO_2 emissions are reduced by about 40-90% from mobile and stationary sources (Alcano *et al.*, 1987, SOLEC, 2009, Mayerhofer *et al.*, 2002, Vestreng, 2001).

Adsorption of chemical materials

Researchers (Stigliani 1988, Sparks R, Nawab A et al., 2003, Sassman S.A *et al.*, 2004) identified four possible pathways of chemicals and their degradation products when they are introduced into the soil. The pathways which are illustrated in Fig.4 are:

1. Rapid leaching through the soil into ground and surface waters
2. Crop uptake
3. Volatization into the atmosphere
4. Retention and storage in the soil

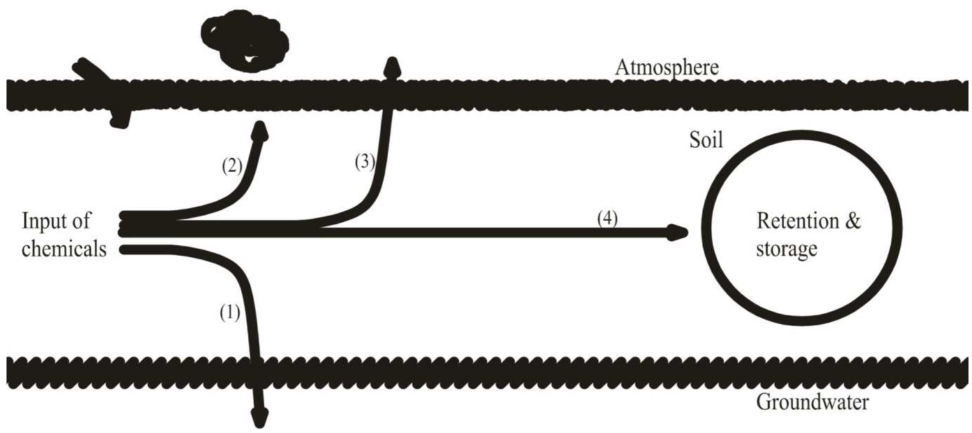

Fig. 4.

Pathways of chemical inputs to soils, pathways 1 is a Rapid Leaching through soil into water courses, 2 is Uptake by Plants, 3 is Volatization to Atmosphere and 4 is Storage and Retention in soil.
Source: Stigliani 1988

The observable effects of chemicals that follow the first three pathways occur quickly unlike the fourth which has a great potential for non- linear and time- delayed environmental effects (Prechtel *et al.*, 2001). Certain toxic materials are retained in the soil and they are not released into the environment until when a certain threshold level is reached. As stated previously, sediment acts as a sink for pollutants. Environmental contaminants such as hydrocarbons, heavy metals and pesticides have been known to have direct toxic effects when released into the aquatic environment (Forstner *et al.*, 1998; Fleeger *et al.*, 2003). There is a direct link between surface water and sediment contamination. Accumulated heavy metals or organic pollutants in sediment could be released back into the water with deleterious effects on the ecosystem. When for example, large quantities of fertilizers containing nitrogen and phosphorus are added to soil to sustain crop yields, much of the nitrogen are lost to the environment as it leaches rapidly through the soil into ground and surface waters and also by soil denitrification processes which by itself is a potential hazard. Nitrate (NO_3^-) in drinking water can cause methemoglobinemia in babies and ruminants because in their stomach conversion of nitrate to nitrite is possible which can act on the blood haemoglobin to form methemoglobin. In contrast, phosphates get strongly absorbed to the surfaces of soil particles. 60% of phosphorus applied to the soil is retained in this way, so if fertilizer application is intensifies, a point is reached when the soil get saturated with phosphorus. All soils have a definite ability to store phosphorus. This ability is defined quantitatively by an index called Phosphate Sorption Capacity (PSC). A subsequent addition of phosphorus after the PSC is reached results in leakage of phosphorus from the soil into ground and surface waters. The time delayed before this stage is reached is strongly dependent on the rate of input of phosphorus and the size of the area to which it is applied. Soil type (its porosity, permeability and drainage rates) and level of water also affect PSC. Phosphorus leakage is the principal cause of eutrophication of waterbodies in temperate climates where phosphorus is the limiting nutrient. In the tropics, nitrogen is the limiting nutrient in fresh water ecosystems, so eutrophication occurs much more quickly in tropical lakes than temperate lakes as a result of fertilizer application to watershed soils. It is certain that in future, the PSC of watershed soils in the tropics would be reached and phosphorus leakage would compound the problem of eutrophication.

In addition to phosphorus, toxic materials from contaminated fertilizers and organic pesticides also get adsorbed to soil substrates. Soil types and other physiochemical conditions interact in a complex way to determine the mechanism of retention of these toxic materials in the soil. For example, heavy metals are exchanged for cations like calcium and as soon as their sorption capacities are reached, these toxic materials become available for uptake by edible plants. Soils that have been extensively cultivated and heavily fertilized are bound to have low sorption capacities for heavy metals, organic pesticides and other contaminants. This is because high inputs of nitrogen fertilizers and removal of crops make the soil more acidic thereby aggravating acidification problems caused by acid deposition from combustion of fossil fuels. Crops grown on acid soils therefore continue to take up and accumulate contaminants long after they have been introduced into the soil. This is another example of time- delayed disbenefit of human activities. A way to ameliorate acidification effects is to apply lime. Liming is the addition of calcium primarily {$CaCO_3$} to neutralise acidity in water or soil and buffer them from rapid flocculation in pH. This is because the hydroxides of many heavy metals are insoluble; when their pHs are adjusted insoluble form precipitate. This is however not cost effective, most especially for small scale subsistence farmers in the tropics.

Oxygen donation

All living organisms require oxygen for biochemical energy production. The ability of microorganisms in both soil and water to utilize molecular oxygen for this purpose is limited as a result of the relatively low solubility of oxygen- containing compounds for oxygen. Such compounds in the soil and sediments are nitrates NO_3^-, Sulphates SO_4^{2-} and Carbonates CO_3^{2-}. The oxidation efficiencies otherwise called potential of these radicals differ hence extraction of oxygen from them by microorganisms occurs in a stepwise fashion beginning with the radical with the highest redox potential.

In a relatively unpolluted waterbody or waterlogged soil, carbon level is below 4mg/L and molecular oxygen is available to break carbohydrate to carbon dioxide and water in an energy releasing process inside the microorganism (Respiration). If extensive organic matter e.g. from sewage is introduced to the waterbody or waterlogged soil, carbon exceeds 4mg/L and a drop in redox potential occurs and microorganisms start to obtain oxygen for respiration from nitrates (see fig.5).

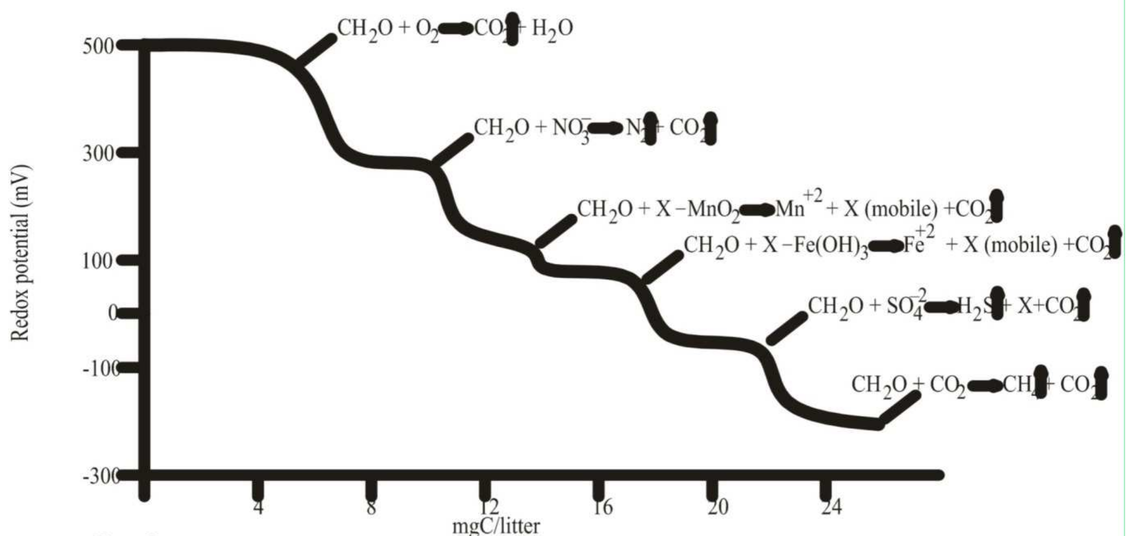

Fig. 5.

Schematic representation of the order in which microorganisms select oxygen-bearing molecules for oxidation of organic carbon to carbon dioxide in oxygen-deficient environments.
Source :Stigliani 1988

Nitrogen and carbon dioxide are given off in the process of nitrate reduction. If the sewage contains industrial effluents, toxic materials such as heavy metals or pesticides, it forms complexes with manganese, aluminium or iron oxides present in the waterlogged soil. As redox potential reduces further, oxygen demands shift to the complexes formed by the toxic materials designated as X (in Fig 5) and manganese, aluminium or iron oxides with a consequent release of carbon dioxide and the heavy metals. As carbon levels approaches 30mg/L, sulphate and carbon dioxide discharge of toxic substances into sea water does not have any immediate deleterious effect on marine life because they are transported to the sediments and immobilised. If cleaner effluents are subsequently discharged into previously contaminated seawater, the resulting increased acidity (pH) and redox potential (Eh) of the seawater will favour the solubility of the previously immobilised toxic heavy metal and other contaminants. Cadmium for example is a heavy metal that exists in the water in soluble form as Cd^{2+} at low pH and a high redox potential (see fig. 6).

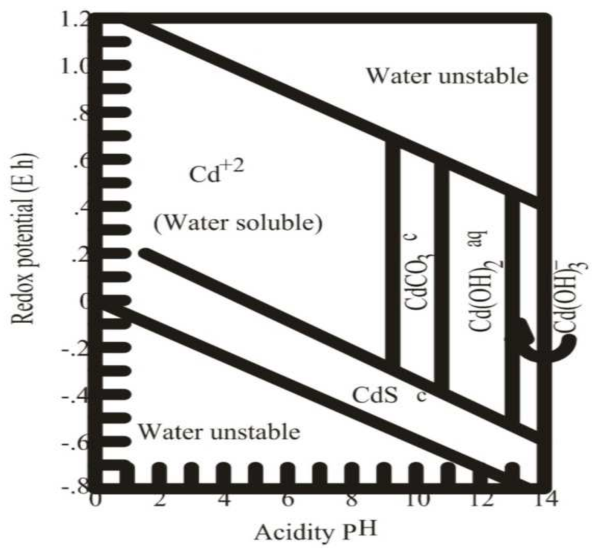

Fig. 6.

Fields of stability of solids (signified by c) and predominant dissolved cadmium species in system Cd+ CO_2 +S +H_2O at 250^OC and 1 atm . In relation to redox potential (Eh) and pH Dissolved cadmium activity, 10-7.05mol/L, dissolved CO_2 and S species, 10-3 mol/L
Source: Hem 1972

Although every heavy metal has its own unique chemistry, their Eh-pH curve revealed that increased acidity and redox potential favours the stability of the water soluble ions (Schuilling *et al.*, 1988, Delai Sun *et al.*, 2001, King, 2006). For example, in the Honnedaga Lake lies in the southwest of the Adirondack, acid rain has killed nearly all of its fish. As acid rain leaches toxic metals like Al from rocks, sediment, and decaying plants where it otherwise would have remained in a harmless state, the fishes unable to absorb oxygen because of increase in acidity slowly suffocate. This phenomenon explains the observed worsening of pollution problems after abatement measures. A lesson to be learnt from this is that time- delayed effect of pollution could be triggered off by abatement measures. This is one of the reasons why pollution is best controlled by avoiding it completely *(Prevention is better than cure).*

Management of surprises
Ecological changes that may occur over a period of time that is short relative to the response time required for implementing mitigation strategies have been termed ‘ surprises’ by Stigliani(1988). Such changes are brought about by activities like energy use and agricultural, industrial, commercial and domestic activities. Usually policy makers and the general public alike always expect that corrective measures should be followed by an improvement rather than a worsening of the unwanted conditions. In reality, this may not occur and it is a source of frustration to policy makers. In order to avoid such frustrations, strategies for managing long-term environmental changes must be developed in such a way that ‘surprises’ are anticipated. One of such strategies employed a two-dimensional matrix that identifies the sources of environmental change on one axis and a small set of CEIs on the other. According to Clark (1986), the advantages of this method include the following:

1. Incorporation of the synoptic approach to complex inter-relationship between economic development and environmental change and;
2. Ease of analysis as a result of condensation of the number of indicators to a definite and small set.

This method identifies both the primary and secondary linkages between development activities and environmental transformations. Secondary linkages occur when a specific development activity affects a given CEI through an intermediate influence of another indicator. The possible primary and secondary interaction between development activities and environments are presented in Table 1.

Table 1. Combined primary and secondary interactions between development and environment. Source. Stigliani (1988).

Consequencies / Sources	Buffering Capacity	Sorption Capacity (Agricultural Soils)	Redox Potential	Toxic Materials Accumulation
Energy Use	1 Acid deposition	2 Energy Use	3 Energy Use	4 Heavy metals, PAHs Increased leaching of metals from terrestial ecosystems as a result of acidification of soils
Agricultural Activities	5 Liming Drainage of wetlands production of Sulphuric acid	6 Phosphate application;cadmium, other heavy metals, pesticides Liming augments sorption capacities; cessation of liming will diminish them	7 Over-Fertilization by nitrate, subsequent discharge to water Disturbance of submerged riparian woods as sink for nitrates	8 Pesticide runoff Accumulation of heavy metals in sediments under low redox conditions caused by nitrates leaching to water bodies
Industrial Activities	9	10	11 Heavy metals toxic organic chemicals	12 Heavy metals toxic organic chemicals Accumulation of heavy metals in sediments under low redox conditions caused by discharge of chemical with high COD
Commercial and Domestic Activities	13	14	15 Discharge to water of organic carbon chemicals with high COD	16 Heavy metals toxic organic chemicals Accumulation of heavy metals in sediments under low redox conditions caused by discharge of chemical with high COD

* Text under double lines describes secondry interactions

Interactions from energy use:

One primary effect of energy use on a CEI is that burning of fossil fuels in energy production processes causes a depletion of buffering capacities of soil through acid deposition defined as indirect effect of sulphur and nitrogen pollutants that are discharged into the environment by industrial activities. So also, Polynuclear Aromatic Hydrocarbon (PAH) and heavy metals (Pb, Cd, Ni, V, Cu) which are contained in trace quantities in the fossil fuels are volatized during combustion and transported through the atmosphere before they are deposited in the environment. As soil become more acidic, toxic heavy metals are leached from soils into groundwater and surface waters and they also become available for plant uptake. This is a secondary interaction between energy use and a CEI.

Interaction from agricultural activities:

Drainage of wetlands that are rich in S increases the redox potentials of soil thereby causing oxidation of sulphides to sulphates. Local conditions such as acid deposition and presence of pyrite minerals (FeS) may cause the sulphate to be flushed out as sulphuric acid (H_2SO_4) thereby causing rapid acidification of soils and subsequent acidification of receiving waters. This phenomenon has occurred in Lake Blamissusion in Sweden (Renberg, 1986). When phosphate fertilizers are used to reduce the sorption capacity of agricultural soil, cadmium is inadvertently introduced into the soil as an impurity. Phosphate fertilizer has varying amount of Cadmium and other metals from the Rock Phosphate (RP). In nature Cadmium (Cd) and Zinc (Zn) are highly associated. Other heavy metals also accumulate in the soil as contaminated manure and sewage sludges are used as fertilisers and pesticides to control pests. Although these conditions are ameliorated by liming, they encourage run-off into water courses and seepage into groundwater this is because while the major plant nutrient added with sludge for example are subject to the plant removal and leaching, the heavy metals will remain in the soil for a much longer period of time. The accumulation of metals in soils thus becomes a long – term potential for phytotoxicity.

Interaction from domestic and commercial (municipal) activities:

Day-to-day activities of man in the non-industrial sector most especially in the thickly populated industrial areas generate a lot of waste which also places a very high demand on receiving waterbodies. Like industrial waste, domestic and commercial (municipal) sewage increase BOD or COD of water bodies and as a result produce anoxic conditions. In places where refuse is burnt indiscriminately, toxic chemicals are released into the atmosphere. Dioxins and PAEs for example are released into the atmosphere when plastics are burnt in open dump sites. Other toxic materials which are usually released into the environment during the dissipative end use of certain consumer products like pharmaceuticals and personal care products eventually find their ways into sediments from where low or high redox potentials can either encourage or discourage their release into aquatic ecosystem. In freshwaters, low redox potential encourages mobilisation while in estuarine ecosystems, the reverse occurs (Stigliani, 1988, Ohlinger *et al.*,2000, Alewel *et al.*,2000,Armbruster 1998, Manderscheid *et al.*,2000).

Future outlook of the environment

Scientists believe that the present changes in the environment should not be attributed to anthropogenic events alone. Francis, (1994) do not agree totally with Stigliani (1988) that our generation has created an environmental 'time bomb' whose tickling has already started. These scientists however found it extremely difficult not to admit that the rate at which the following changes in the environment continue to occur has been increasing in the past decades despite attempts to stop or reduce them:

- Acidification of the soil
- Saturation of soils by phosphates and subsequent leaching into the ground and surface waters

- Anoxic conditions and emissions of H_2S in coastal waters
- Bleeding of toxic heavy metals from contaminated estuaries sediments
- Release of toxic metals from agricultural soil and
- Changes in soil redox conditions due to drying – up of wetland and moisturisation of dry lands.

These changes suggest that mankind has started reaping the disbenefits of socio-economic development which in the past provided rapid short –term economic benefits (see Fig.3).

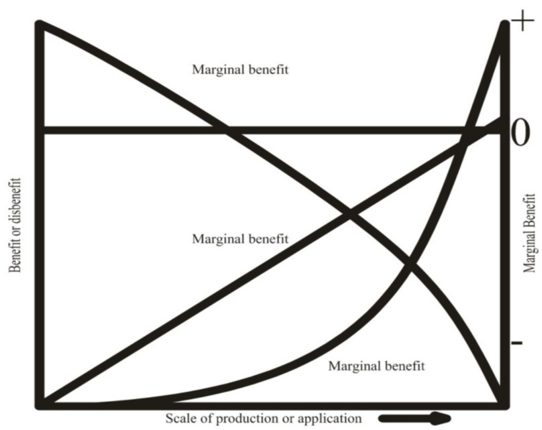

Fig. 3.

Variation of benefits and disbenefits of a technology with scale of production. The net marginal benefit is a derivative of the difference between the benefit and disbenefits curves. Source: Brooks 1986

The most disturbing aspect of this development is that adjustments in such certain cases are too late because the environmental degradation in question may be irreversible. It seems as if our obligation to future generations is to stop the tickling of the 'bomb' by evolving a monitoring system with early warning potential of environmental threats. This is an essential component of long –term strategic planning for the ecological sustainability of the environment.

Environmental monitoring system:

There is no direct linkage between cause and effect for ecological changes that are delayed in time in respect to the source of change. This is because the source of pollution acts on the environment through intermediate step. This step generally involves a depletion of an environmental attribute through the accumulation of the pollutant. Because this depletion appears as a slowly changing variable in time, it offers itself for monitoring and possible manipulation in order to avert the ecological change or surprise it may lead to. The history of acidification of the Big Moose Lake described earlier can be used to illustrate this phenomenon. Data on SO_2 emissions, pH of the lake and fish species population are all inadequate to predict future of acidity of the lake. Rather, the buffering capacity of the watershed soil alone is the key indicator of future levels of acidity of the lake. This buffering capacity depleted slowly and gradually for 70 years before the effect on human activities on Lake Acidification was observed (see figs. 7a and 7b)

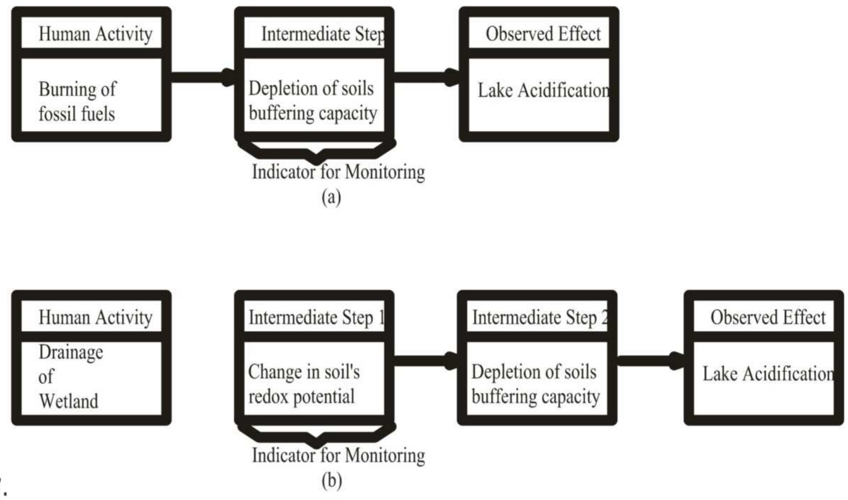

Fig. 7.

Illustration of linkages between human activity (cause) and lake acidification (effect).(a) simple linkage (b) complex linkage

For an environmental monitoring programme to effectively provide early warnings of fundamental ecological changes, its formulation should incorporate the following considerations:

1. The size of the system's reservoir and the inputs of pollutants over time should be determined in cases where accumulations and storage of pollutants occur slowly.
2. Indicators and the final effects should be quantified so as to be able to predict the time scale over which the system may become saturated. For multi- step processes involving several intermediate linkages, the coupling between the indicator and other intermediate processes must be understood.
3. If changes in certain chemical conditions cause a sudden shrinkage in an ecosystem's storage capacity for a given pollutant, these changes should be monitored through the measurement of the appropriate chemical parameters (e.g. pH in agricultural soils and redox potentials in aquatic ecosystems). The input pollutant should also be simultaneously monitored.

The 'bottom- up' approach

Policy makers are usually interested in changes observed in the most vulnerable areas because these changes provide early warning of sudden ecological changes. However, when trying to anticipate problems that do not currently exists, it may not be possible to uncover vulnerabilities by judging from pollutant inputs or degree of sensitivity of pollutants alone. In this situation attention is focused on the possible impact of the pollutant on the environment. Environmental factors that may influence the impact and the conditions under which the factors could change in future are also identified. This approach is termed the 'bottom-up' approach because it attempts to tackle the problem right from its cause unlike the 'top-down' approach which tackles the problem from its effects. The sensitive factors that influence certain CEIs and the scenarios under which the factors could change in future are illustrated in Fig.8.

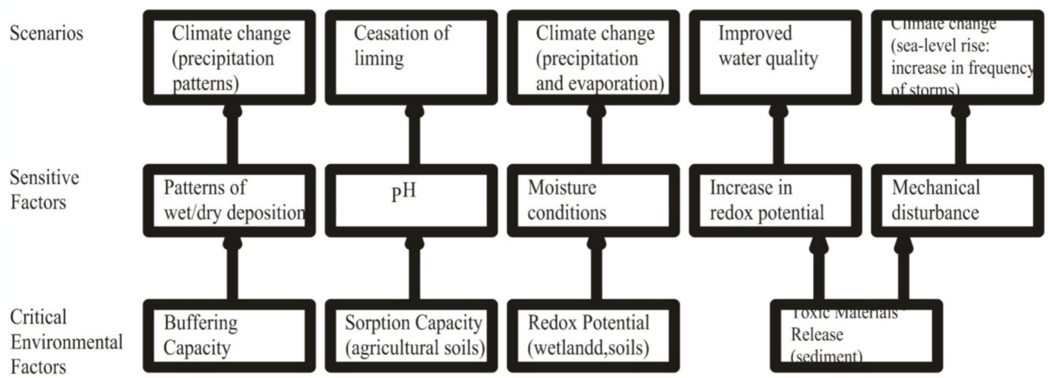

Fig. 8.

Illustration of the' bottom –up approach'

Patterns of rainfall and wind direction affect acid deposition (and therefore buffering capacity) which may be affected by climatic change as it relates to changes in precipitation patterns. So also, sorption capacities are very sensitive to acidity (pH) which in turn may increase in the future in soils of abandoned farmlands where liming has ceased. Redox conditions in soil and wetlands could also change markedly as a result of alterations in moisture conditions due to climatic change. Finally, redox conditions in waterbodies and mechanical disturbance of sediments are factors that influence release of toxic heavy metals that were previously immobilized in the sediments. Two future events that could influence these factors are improved water quality and the impending sea level rise and increase in the frequency of storms (Hekstra , 1990, Wilander A *et al*.,2000, Johanessen T, 1995).

One advantage of the 'bottom –up' approach is that it raises questions that help to channel the thought of researchers in the fields of water quality management, agricultural pollution and climatic change in the direction that is applicable to long-terms impacts on critical environmental indicators. This is no doubt one path that cannot be faulted when viewed from the perspective of our generation trying to fulfil our obligations to future generations in terms of responsible stewardship of the environment now commonly referred to as Sustainable Development, that contextualises development that meets the need of the present without compromising the ability of future generations to meet their own needs.

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