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Pit lakes as an end use of mining: A review

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Abstract

A theoretical review of ‘‘mining pit lakes’’ indicates that, like natural lakes, such lakes display a huge diversity. They are typically in a non-equilibrium state with respect to their surroundings. While reviewing the pit lakes, which are to be used as an end use of mine, one must consider the various related aspects such as closure planning of mines, subsidence effect of mining and water quality. At the decommissioning phase of mining operation, a detailed technical study is required on different aspects of such created water bodies considering their morphometry, geology, hydrology, water quality (geo-chemistry), rate of filling, and biology. Pit lakes have their value as resources for miscellaneous purposes, e.g. recreation, fisheries, water supply, and wildlife habitat, which is dependent mostly on their topography, location water use and safety characteristics. Internationally, pit lakes, as self-sustaining aquatic ecosystems, have been developed in the past, e.g. Alberta Pit Lake in Canada, Sleeper pit lake, Nevada USA and Westfield pit lake, Scotland. In Indian mining industry neither scientific studies nor case record of mining pit lake development is available because after cessation of mining operation, the mine is left to reclaim naturally and no end use of the mine area is practiced. Recently, ‘mine closure plans’ are introduced and care is taken for mine sites at their end phase scientifically. One such attempt in India at ‘Kerendari coal mine’ in Jharkhand state is a laudable and new attempt. In brief, since the opportunities for the development of ‘mining pit lakes’ are enormous in future, this review will be useful particularly in those countries and for those companies, which have a number of old surface mines heading towards the decommissioning phase. The review done here can be practically utilized for the evaluation and assessment of new project clearances and statuary compliance purposes.

Keywords: *Pit Lakes, Mining, Coal Mining, End Use of Mining, Mine Closure Plan.*

1. Introduction

Open-pit mining results in residual pits, overburden or waste rock piles, and sometimes tailings impoundments left on the landscape. Different kinds of mines produce pits with various physical, geochemical, and ecological characteristics. Pits from mining of chemically inert materials (inert materials include sand, gravel, clay, bentonite and limestone) tend to mirror the geo-chemistry of their surroundings. ‘Pit lakes’ are often confused with ‘normal lakes’ which are formed as a result of water filling in a depression. In this paper only ‘mining pit lakes’ are reviewed. ‘Mining pit lake’ (in this paper also referred as ‘pit lake’ / ‘pit lakes’) is one which is backfilled. Other mine impoundments, such as tailings ponds, are not included in this definition.

International review of literature about ‘pit lakes’ indicates that they were developed in the past as self sustaining aquatic ecosystems e.g. Alberta Pit Lake in Canada [1, 2]; Sleeper pit lake [3] and Westfield pit lake, Scotland [4]. Pit lakes have their value as resources for miscellaneous purposes beginning from. Recreation to fisheries and water supply to wildlife habitat which is dependent mostly on their topography, location water use and safety characteristics. While reviewing the pit lakes which are to be used as an end use of mine, one must also consider the various related aspects, e.g. closure planning of mines, subsidence effect of mining and water quality.

Since pit lakes are created water bodies formed by artificial flooding, or allowing the pits to fill naturally through hydrological processes such as precipitation or ground water infiltration, they are to be in tune with the mine closure plan of the company who has the responsibility of implementing decommissioning operation of mine. The mine closure plans (progressive and final) was first introduced in India in 2003 [6] as a legal statute though several other mineral producing countries namely Australia, USA, Canada, Chile, Papua New Guinea, Bolivia, Japan,Spain and many European countries were already having such plans in place [7, 8]. Since the basic objective of mine closure is to leave the excavated site in safe, stable and good environmental conditions, the amalgamation of closure planning and end use of mine pit in the form of a water body is relevant and serves a supportive purpose for scientific planning [9]. A comprehensive review of pit lakes and mine closure have been made to help the reader to know in details about this vital correlation between closure and end sue of mining land including its design and development [10].

The results of surface subsidence investigations carried out in different coalfields in India are presented in literature [11]. Since Indian coal mining is mostly under shallow to moderate cover, several cases of discontinuous subsidence have been observed in coal mines. Mine subsidence studies at the Central Institute of Mining and Fuel Research (CIMFR), Dhanbad have been going on for the last 35 years in different coalfields of India. The principal method of coal extraction that is 'open pit' and 'underground methods' involves subsidence phenomenon. According to the method of mining, the effect of mining on subsidence should be investigated and considered as one evaluation parameter for pit lake feasibility evaluation. Thus, this review shows that by utilizing the different tools available for subsidence prediction and modelling, the end pit lakes can be planned more safely and scientifically.

It is significant to note while reviewing, that pit lakes have long-term benefits as a 'water resource' for industrial or other activities. Hence, the quality of water contained in it is important and their environmental reclamation is usually required to keep them biological active. It is anticipated that surface coal mining 'pit lakes' formed at the closure of mining may create environmental problems [5]. Since the coal has natural tendency of forming Acid mine drainage (AMD) and other excavated mine pit of metallic ores has the pollution tendency, water quality parameters must be in the permissible limit. This is achievable by planned management measures. Remediation and management options for decommissioned lignite mines of former East Germany can be extremely helpful in this context [12].

Such excavated pits are of various depths and sizes and not in an equilibrium state like natural lakes. Their water environment is economically manageable by long term measures and scene can be set for pit lake development.

2. Key aspects of pit lakes/ Mining pit lakes/ End pit lakes

Comprehensive review of theoretical aspects of pit lakes in brief can be done considering historical analysis, current practices, their characteristics types and classification etc. With respect to 'mining pit lakes' detailed review is done by Soni and Singh [13]. It is significant to note here that development of such end pit lakes in 'metallic mines' and 'coal mines' differs greatly. The mineral mined, has a close linkages with the pit water quality. Therefore, hydrology, limnology, chemistry and biology of such pit lakes are reviewed and described below in brief to get a 'clear and concise' picture of the environment in the mined out area in future.

2.1. Hydrology of pit lakes

Hydrology determines how rapidly open pit mines fill with water after closure, and also influence the final steady state water budget of the lake that is formed. As described by [14], most large open pits will eventually intersects the water table during mining and consequently steps must be taken to dewater the pit during operation. After mining ceases, the dewatering pumps are usually shut- down, allowing the water tables to rebound and in some cases a pit lake is formed or created. A generalized water balance Equation for a pit lake can be summarized as follows:

$$P + SWin + GWin = E + (T) + SWout + GWout \pm \Delta S \quad (1)$$

Where

- P= direct precipitation falling on the surface of lake;

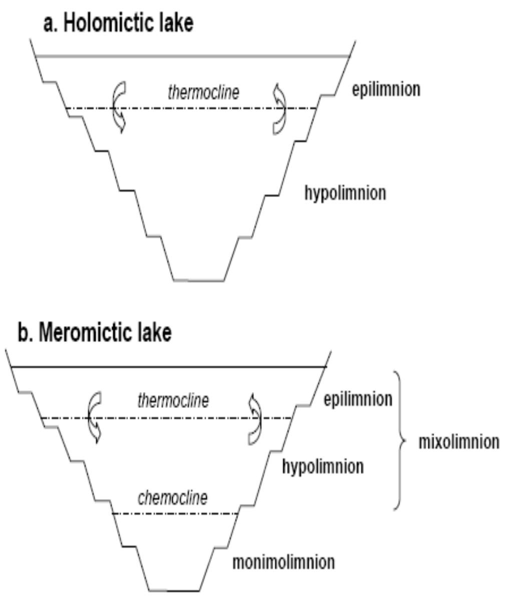
- SWin= sum of any surface water inputs such as diverted streams, storm-flow; pit-wall runoff, or waste water being disposed of in the lake;
- GWin= groundwater entering the lake;
- E= evaporation;
- T= plant transpiration (in parentheses because it is expected to be a minimal term for most pit lakes);
- SWout= surface water exiting the system (including water that is pumped, treated, and discharged to receiving water bodies);
- GWout= groundwater exiting the lake and
- ΔS= change in storage, i.e., the volume of water in the lake.

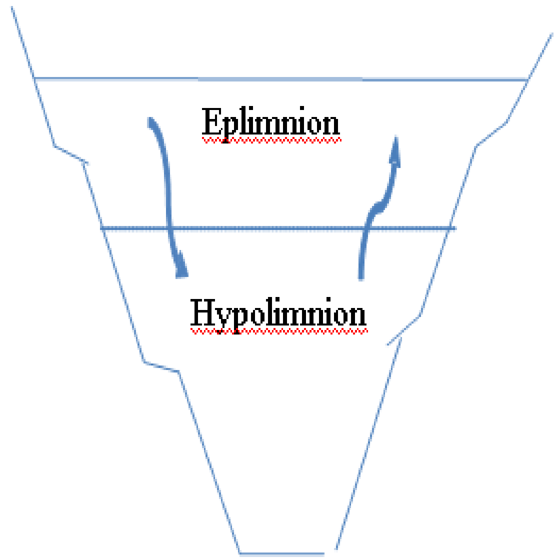
Terms on the left side of Equation (1) are water inputs, whereas terms on the right side (with exception of ΔS) are water outputs. If input > output, then ΔS is positive, and the lake volume will increase. Geological setting and rock types typically contribute to the hydro-geological aspects.

2.2. Limnology of pit lakes

For any pit lake, its *limnology* is important. The vertical structure of the lake and whether it is conducive to seasonal changes is what is called as 'turnover'. According to this turn over, pit lakes are classified as 'holomicticlake'or a 'meromictic lake'. In these lakes, separate zones of seasonal mixing (depending on temperature, density and depth) are denoted (Figure 1). Wherever the temperature changes very harshly and abruptly and according to the season, the vertical structure of the lake changes, this assumes significant importance in certain climates. In many countries, e.g. India, Iran, Australia, South Africa etc., the climatic conditions are such that they may not be of very much significance but in case of extreme harsh climate like Canada or Scandinavian countries, which has cold weather conditions during maximum period of the year, they are extremely important from vertical stratification angle as it is essential for survival of fauna/ biological life.

Most natural lakes in tropical climates are holomictic, meaning that they typically undergo a complete top-to-bottom turnover. When surface water temperature passes through these dense layers (maximum of ~ 4°C) holomictic lakes become vertically stratified in the summer, with a warmer, less dense "epilimnion" resting on top of a colder, denser "hypolimnion". These two layers are separated by a thermocline (also known as the "metalimnion") i.e. a zone of rapid temperature change with depth. These vertical mixing of lake water is driven by surface waves, episodic influx of groundwater [15, 16]. Heat can be added to the bottom water either from the surrounding rocks (most continental settings have geothermal gradients of ~ 20 to 35°C/km) or from influent warm ground water, or both.





Arrows denote the zone of mixing

Figure 1. Classification of pit lakes according to limnology.

Thus, lake stratification or vertical structure of lake/ water body is important from ecology and limnology view point. In general, the water density, the effect of changes in temperature and the effect of changes in salinity (from upper layer to lower layer) are significant for the mining pit lake (s).

2.3. Chemistry of pit lakes

Mining pit lakes, display a wide diversity in water quality and dependent on the mineral deposits that were extracted. General trends in pit lake chemistry have been reviewed by several researchers [17, 18, 19, 20] and they reflect a wide complexity from the chemical analysis angle. Many pit lakes from former coal mines contain elevated concentrations of heavy metals (e.g., Al, Cd, Cu, Fe, Mn, Ni, Pb, Zn, U) and/or metalloids (e.g., As, Sb, Se, Te) that can pose a threat to the environment. In contrast, pit lakes formed from mining of iron ore, limestone, bauxite, copper ore, gravel or industrial minerals (e.g., talc, asbestos) may have other dissolved metals concentrations depending on the ore type. Depending on the end-use of a particular pit lake the water quality parameters such as salinity, turbidity, DO concentration and nutrient content become important. Therefore, pit lake chemistry plays a significant role in water pollution control and management. A brief review about this is as described below.

pH: The single most important parameter that controls pit lake water quality is pH. This is because the mobility of most metals and metalloids is strongly pH-dependent. In addition, most aquatic life forms have relatively narrow ranges of pH tolerance. As shown by [17] pit lakes that are strongly acidic ($pH < 4$) tend to have high concentrations of “cationic” trace metals, such as Al3+, Cu2+, Fe2+/Fe3+, Mn2+, and Zn2+, in addition to high concentrations of the common cations Ca2+, Mg2+, Na+ and K+. In low-pH lakes, the dominant anion is usually sulfate (SO_4 2- or HSO_4 -). In contrast, pit lakes that have near-neutral to alkaline pH tend to have relatively low concentrations of cationic trace metals, and may contain appreciable bicarbonate (HCO_3 -) in addition to dissolved sulfate. Alkaline lakes may be highly elevated in metalloids, such as As or Se, present as dissolved anions such as $HAsO_4$ 2- or SeO_4 2- [17]. Although these general trends exist, each mineral deposit is different and needs to be evaluated on a case-by-case basis.

TDS & TSS: Higher TDS (total dissolved solids) values are of general occurrence in most of the mine water and pit lake water. This may be attributed to the leaching of soluble salts through pit walls and evapo-concentration. In limestone mines higher TDS concentration is often recorded which is due to pit wall contact reason only. pH has less influence on the relatively high TDS of pit lake water.
Total suspended solids (TSS) is also a common characteristic of mining pit lakes, due to rapid physical erosion of steep mine walls combined with wave action along shorelines during stormy periods.

Turbidity: This has a negative effect on the primary productivity of the water body as it decreases the transparency of the water column, hence, reduction in the propagation of photo-synthetically active radiation in the water body. Another common source of turbidity in iron ore pits is oxidation of dissolved iron to hydrous ferric oxide (HFO), a red-brown substance that is very fine-grained and slow to settle by gravity. Sometimes the word ‘Elevated turbidity’ is used for TSS.

Dissolved Oxygen (DO): DO is essential for many forms of aquatic life, in particular fishes. A great majority of water bodies have profile of dissolved oxygen (DO) decreasing along the depth of the water body. Atmospheric oxygen gets dissolved at the surface under the influence of wind and wave motion. Most pit lakes contain elevated DO levels in shallow water. However, with the increasing depth, many pit lakes are susceptible to depletions in DO, and this is aggravated by the often higher chemical oxygen demand (COD) of mining lakes as compared to natural lakes. Mine pit lakes pose few oxidation reactions that work as a sink for DO. For example, in hypolimnion oxidation of pyrite and other metal sulfides on submerged mine walls and oxidation of dissolved ferrous iron (Fe^{2+}) provides a long-term sink for dissolved oxygen in stratified pit lakes.

Geochemical processes taking place in mining pit lakes are reviewed by [5, 21] and recently by [22, 23]. In a biologically active pit lakes majority of processes were triggered by intensity and duration of solar radiation available to the lake most important among them is Evaporation and Photosynthesis. Wind velocity also plays an important role. Biological entities like microbes mediate some important chemical processes (Figure 2). There are several other chemical reactions that take place in mining pit lakes and have been explained scientifically in published literature. This includes the followings:

(a) Leaching of soluble salts from bed rocks e.g. precipitation of hydrous ferric oxide, adsorption of trace solute on HFO etc.
(b) Sub-aqueous water-rock interaction e.g. pyrite oxidation in coal having sulphur content.
(c) Bacterial reduction of iron and sulphate.

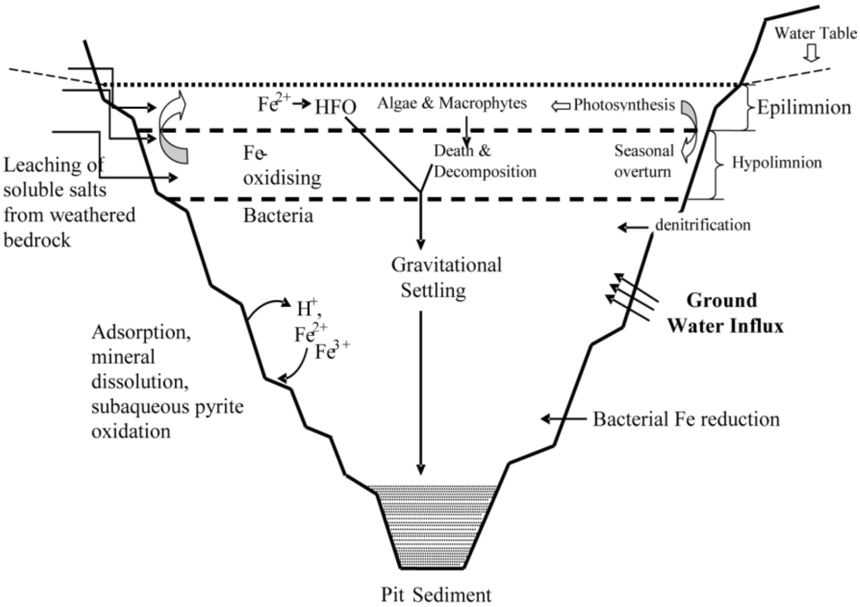


Figure 2. Summary of chemical processes occurring in mining pit lakes.

Nutrient richness of water bodies can be correlated with the strength of bio-geochemical cycles and inputs from the surroundings. Most of the young pit lakes, irrespective of water source, are poor in terms of nutrient concentrations, hence, termed as oligotrophic (i.e. nutrient-poor). Another important aspect for low concentration is the high volume to surface area ratio of pit lakes. Chemical and/or biological reactions may sequester nutrients in near-surface water and store them in sediment at the bottom of the lake. Extremely low nutrient concentrations will limit primary production by algae and aquatic plants, which can leave a lake relatively barren with respect to higher forms of aquatic life. Sometimes remains of explosives may initially cause high nitrate concentrations in the pit.

Thus, pits created from coal and metallic minerals mining are more strongly affected by the chemistry of the mined resources e.g. coal /fuel mineral deposits commonly contain pyrite (FeS_2), which reacts with atmospheric oxygen and water to generate sulfuric acid [24] and termed as ‘Acid Mine Drainage/Acid Rock Drainage’ in mining terminology.

2.4. Biology of pit lakes

Biology of pit lakes is one of the most important factors in the establishment of a water body. Biological life in a water body depends upon various attributes. One major attribute is sustainable existence of bio-geo-chemical cycle in aquatic ecosystem. Key water quality parameters responsible for a biologically active aquatic body are pH, temperature, transparency, nutrient status etc. [21]. A survey of aquatic plans and fauna of the study region is therefore required to know the richness of aquatic bio-diversity. It is hard to find any information regarding biological characteristics of mining pit lakes in India; as such water systems in closed mines are a new phenomenon for the industry. Internationally too, there is limited information available regarding the biological characteristics of mining systems.

Since pit lakes are often contaminated with trace elements and/or low pH, the ecological balance of pit lakes, is disturbed biologically endangering the various aquatic life forms [25]. Generally, the species diversity of any constructed water body is highly influenced by the specific natural biological diversity that persists in other water bodies in the vicinity. It is explained in literature that biocenoses in pit lakes [26, 27] will be dependent on various and complex factors including how the lake was filled and the initial physical and chemical conditions of the water body. Pit lakes are initially in stressful conditions (after first inundation) as quite stressful resulting in poor biological diversity, especially at higher trophic levels [28, 29]. The basic habitat conditions like transparency, metal concentrations, nutrient levels, and pH are disturbed. In addition, sometimes the surrounding terrain or geography is not much supportive due to steep / harsh slope; hence, littoral zone is not supportive for macrophytic colonization. The lack of this productive habitat will limit the establishment of aquatic vegetation and therefore micro- and macro-invertebrates, fishes, and other wildlife.

Because of these characteristics, pit lakes tend to have limited biological activity and chemical interactions dominate [30]. Therefore, the biological community of a newly formed pit lake may differ markedly from that of natural lakes in the same area, with diversity and abundance being much lower in the former [28]. With the passage of time and influence of prevailing natural phenomenon many of these characteristics change. With time and after lake formation, the biological diversity will be different depending on the age of the water body, with more taxa (a population, or group of populations of organisms) being present in older lakes [31]. Thus, a water body can be considered stable or biologically active when it sustains diverse aquatic life, i.e., aquatic flora and fauna. Co-existence of flora and fauna in a water body defines the structural and functional components of aquatic ecosystem.

3. Development of water bodies in open cast mining areas

Technical considerations that are important for the development of water bodies in open cast mining areas are not only ecological but economical as well. Since the aquatic life is survived under specified condition the optimum depth of pit-lake for its biological activeness needs to be assessed or scientifically evaluated. It should also be critically observed whether the development of pit-lake is an economical proposition or other end use of mining, are cost effective. In the following paragraphs some points which are practically important in respect of water bodies in open cast mining areas including their management, economics and optimum depth for development will be reviewed

3.1. Pit lake ecology: management and analysis

Fresh-water ecology emphasizes the organism-environment relationship with respect to fresh-water habitats in the context of ecosystem principles. 'Freshwater habitats' namely Lentic (or standing water habitats i.e. lakes, ponds swamps or bog) occupy a relatively small portion of the earth's surface as compared to marine or terrestrial habitats but their importance is far greater than their area. Ecological study of fresh water in all their aspects i.e. physical, chemical, geological is therefore essential for scientific analysis.

To restore the land utilized by mining and allied activities to its normal and near normal conditions, the help of 'pit lake development' can be taken as it helps in the management of ecological status of degraded land of mineral or fossil fuel bearing areas. The development of surface water bodies must start alongwith the process of 'mine reclamation and restoration' at the decommissioning phase of mine. The restoration shall be done stage-wise and progressively. By establishing first stage of ecological restoration disturbed natural drainage and soil fertility could be stored with time. Presence of water easily establishes the local flora and grassland and help in developing forest species of different varieties. Later stages of 'ecological restoration' slowly build up organic carbon and humus content naturally. Soil being used and an essential constituent for plant growth, in turn transforms the degraded mining land to usable agriculture type land.

The post mining ecological management in the mining areas, to be developed in the form of Pit Lake, depends on the local conditions and should start much before the cessation of mining operation. Broadly and theoretically, these include

1. Backfilling of excavated pit.
2. Preparation of an inventory of aquatic flora as well as aquatic fauna required to restore natural conditions in the mining area.
3. Detailed reclamation and rehabilitation plan (as planned) and its stage wise implementation.
4. Top soil and sub-soil rejuvenation (preserved during initial mining phase) for its productivity and reuse.
5. Reclamation of mined out areas and treatment of areas affected with subsidence.
6. Human interference in closed mining areas be reduced progressively.
7. Protection of endangered and rare species, if observed shall be done meticulously as they are the natural agents of ecological restoration.

Pit lakes as usable water bodies is since the best from ecological restoration view point, the environmental damage caused due to mining can be easily and partially compensated. Pisiculture development in such lakes on commercial scale is adjudged as best use for a coal mining pit. Large number of coal mine pit lakes in Pennsylvania, USA that contain a diverse ecological community, including fishes, are existing [32]. These pit lakes as ecological habitat reflect favorably on the quality of habitat provided by these water bodies. Since pit lakes may in favorable circumstances be capable of supporting a diverse ecological community, the ecological benefits of these lakes especially in terms of habitat creation or restoration and the maintenance of such habitat is immense. A pit lake can be made ecologically sustainable with the establishment of structural and functional attributes required for an aquatic ecosystem. It includes the establishment of tropic levels from primary producers like phytoplankton to top consumers like waterfowl. The strength of ecosystem can be seen in the existence of healthy bio-geo-chemical cycles and its characteristic food chain.

As described earlier also and from ecological point of view, it is significant to note that the biodiversity of a newly-formed pit lake is likely to be low, but is expected to increase with time, and can furthermore be enhanced by re-landscaping the pit walls or treating the contained water, either chemically or biologically. Steep, rocky high walls above the lake surface can be a potential habitat for birds, bats, rodents, and browsing animals etc. There are also possible negative consequences of pit lakes from the standpoint of habitat. For example, in arid, low-latitude regions (Western Australia, SW USA, Africa), pit lakes may be breeding grounds for disease-carrying insects, such as mosquitoes [33, 34]. There is a possibility of eutrophication due to excessive nutrient addition through natural or anthropogenic means.

'Aquaculture' can be another appropriate end use of pit lakes. Pit lakes may in fact be more suitable for aquaculture in comparison to natural lakes since the former usually have no surface connection to any other water body, thereby eliminating the risk of the introduction of non-native fish or other negative consequences of fish farms (e.g., disease, antibiotics, fertilizers) into the surrounding aquatic ecosystem [35, 36]. By virtue of their great depth and (often) meromictic characteristics, pit lakes have the potential to permanently sequester nutrients and decaying organic carbon in benthic sediment, thereby removing sources of biological oxygen demand that otherwise can plague aquaculture practices.

3.2. Economics of pit lakes vis-a vis mine closure

To a considerable extent the economics of pit lake development depends on mining depth developed at the time of mine closure. The cost of pit lake development is directly proportional to the:

(a) Backfilling and earthmoving costs.
(b) Reclamation cost (i.e. the cost for maintaining slopes and leveling).
(c) Cost of water refilling.

A conventional 'shovel-dumper pit', 'shovel-tipper/ truck pit' and 'dragline pit' development cost will be sharply different. Such pit development, if planned, must be done during the operational stage of mine. Working out the pit lake development cost at the time of mine closure is always a significant and worthy exercise, despite the fact that thorough economic analysis of pit lake development is done earlier.

In those cases where the mining depth is more, the backfilling of the excavated pit will be more and necessarily required for biological sustenance of pit lake due to the fact that very deep man made lakes (>500 m deep) becomes biologically inactive and a source of ground water contamination. Wherever backfilled mine pit is not an economic or feasible option and the pit extends into the water table, the deep pit lakes (>250 m deep) can also be developed economically if its scientific remediation is done. Sourcing organic material for pit lake bio-remediation in remote mining regions is a one important challenge [37].

Since water filling in such pit lakes is done both naturally (through rainwater accumulation and rainwater harvesting) and by pumping from available nearby resources, this also adds to the cost economics. Pit lake development cost can be gainfully recovered through commercial utilization of developed pit. "Closure planning fund" for pit lake development is the best option but such funds should be activated right from the beginning of mine.

3.3. Optimum depth of pit lake for biological activeness

Biological activeness or survival of water bodies is quality and depth dependent. Both at shallow depth (<20 m) and deeper depth (>20 m), the biological lives can survive. Several other factors which are site/case-specific determine the sustainability of mine pit lakes. However, it should be noted, that knowing optimum depth at which water-body can remain biologically active, promotes better management practices hence, depth of pit lake is important. It is apprehended that 'pit lake' which has a planned depth of approximately 45 m from ground surface, has less possibility of remaining biologically inactive. With depth, the number of chemical processes took place in the pit lake. A summary of chemical processes occurring in pit lakes has therefore been prepared (Table 1) and the information is arranged depth wise from top to bottom. Thus, optimum depth study is helpful in predictive assessment which can be done by modern day tool of 'computer modelling' available to researchers.

Table 1. Processes and impact for shallow and deep water depth.

(a) DEEP WATER

Process	Impact
Aerobic respiration of organic carbon	Dissolved oxygen is depleted or completely consumed.
Sub-aqueous oxidation of pyrite by dissolved Fe^{3+}	If water is acidic, high concentrations of Fe^{3+} may persist at depth. Fe^{3+} is a strong oxidant of pyrite and other metal sulfides, resulting in a drop in pH and release of Fe^{2+}, sulfate, and other metals.
Microbial reduction of Fe and Mn oxides	Increase in dissolved Fe^{2+} and Mn^{2+} concentration. Increase in pH. May be major cause of high-salinity bottom water that can induce meromixis. May release adsorbed metals and nutrients to water column, such as arsenic and phosphate.
Microbial reduction of nitrate	Reduction of dissolved nitrate (if present) to N_2 and/or ammonia.
Microbial sulfate reduction	Decrease in dissolved sulfate. Increases in hydrogen sulfide (H_2S or HS), pH, and bicarbonate alkalinity. Drastic decrease in concentrations of metals (e.g., Cd, Cu, Fe, Ni, Zn) that form insoluble metal sulfide precipitates. Possible buildup of H_2S (a poisonous gas) to dangerous levels.
Methylation of Hg	If present, inorganic Hg may be concerted to methyl-Hg, resulting in rapid bio-accumulation in organisms.
Methano-genesis	May occur in pit lake sediment with a high organic C to sulfate ratio. Increase in concentrations of dissolved organic carbon, CH_4 and H_2

(b) SHALLOW WATER

Process	Impact
Evaporation	Concentration of all solutes in proportion to the fraction of water lost to vapor. May lead to precipitation of gypsum, calcite, and other sparingly soluble salts.
Photosynthesis by algae, cyanobacteria, and plants	Increase in biomass which provides carbon source for bacteria, animals, and other decomposers. Increase in DO. Increase in pH (for non-acidic lakes). Possible uptake of trace metals by plants. Blockage of sunlight if conditions are eutrophic.
Photo reduction	Photo reduction of Fe^{3+} or hydrous ferric oxide to Fe^{2+}. Possible photo reduction of Mn oxides to Mn^{2+}. Rapid attenuation of visible light, especially at short wavelengths. Catalyst for breakdown of dissolved organic carbon.
Leaching of soluble salts stored above the water line	Increase in salinity and concentrations of trace metals and metalloids
Oxidation and precipitation of hydrous metal oxides	Decrease in concentration of dissolved Fe and Mn. Decrease in trace solutes that adsorb onto hydrous metal oxide (see below). Increased turbidity from suspended mineral particles. Possible drop in pH.
Adsorption onto suspended mineral particles or organic matter	Decrease in concentration of heavy metals and metalloids. Enhanced removal of As, Se at low pH. Enhanced removal of Cd, Cu, Pb, Zn at high pH (Important sink for phosphate).
Dissolution of minerals exposed on submerged mine walls	If carbonate minerals are present, can be an important mechanism for buffering pH to near-neutral conditions. If lake is acidic, may see conversion of feldspar and other rock-forming minerals to clay.
Sub-aqueous oxidation of pyrite by O2 and/or dissolved Fe^{3+}	Increase in concentration of dissolved heavy metals and sulfate. Drop in pH. Drop in dissolved oxygen and/or dissolved Fe^{3+} concentration.

Source: Gammons et al., 2009 [14].

4. Modelling and prediction– A scientific evaluation tool for pit lake

There are methods available and they have been proposed to predict the future water quality characteristics of mining pit lakes. Existing experimental methods / procedure reviewed and available for assessment and prediction includes:

1. Acid-base Accounting Test (ABA test): To quantify the long-term potential for a given rock or waste material to generate acid [38]
2. Kinetic Tests: Kinetic tests are often employed to get more detailed information on the chemistry of mine pit lake water that are likely to be generated in different mine and geological settings. One common procedure is the so-called 'humidity cell test' [39, 40]
3. 'Pit Lake in a Can' Experiments (Mesocosm Experiments): Some simple but useful information to predict future pit lake chemistry can be obtained by gathering representative bulk samples of weathered bedrock from different parts of the pit-wall, crushing the samples to a gravel size, and then leaching with distilled water in the laboratory. This is similar to the leaching procedure used in a humidity cell test [17, 14]
4. Computer Modelling: For future assessment (prediction), modelling and detailed analysis of mining pit lakes, computers are the best available tools these days. Many researchers across the globe have developed models to predict the water quality both biologically and chemically. Because of interdisciplinary nature of assessment and evaluation involving ecology, botany, zoology, geology and mining etc., it is also a bit difficult, if not impossible to review them at full length. However, for long-range predictions, different models available are as follows:

(a) Hydro- geological models namely MODFLOW, SEEP/W [41, 42, 43,44, 45, 46]
(b) Limnological models [47]
(c) Geo-chemical analysis models
(d) Biological models

Similar to MODFLOW, biological, geo-chemical and limnological assessment models for different objectives are developed but they require considerable input data, which are generally not available at the start of the mining. As the mine is developed, such data are collected /gathered progressively. In Indian mining industry such kind of work is limited or can be said as nil. One example that can be described / reviewed is the assessment and prediction of lake turnover.

Predicting the Lake Turnover: Mining pit lakes with high depth to width ratio are less apt to undergo complete lake turnover [27]. The aspect ratio of a given pit lake can be quantified by a term called (Relative Depth or Zr) and calculated as given in Equation 2 below.

$$Z_r(\%) = 50.Z_m.\frac{\sqrt{\Pi}}{\sqrt{A}} \tag{2}$$

Where

Zm = maximum depth and A = Surface area of the lake.

In a survey of mining pit lakes around the world, it is suggested that most artificial lakes with Zr > 25% are meromictic, although there were a few lakes with Zr > 25% that were 'holomictic', and many lakes with Zr < 25% that were 'meromictic'.

5. Post closure hazards

Pit lake development may also pose post-closure hazards, which could be either from external sources or internal sources. These hazards shall be managed properly to protect the ecology of the region and at the same time balance the economics of mine closure which otherwise a non-productive phase of mine. Following are the post closure hazards.

External Hazards:

a. Excessive erosion and soil loss due to natural agents such as precipitation /runoff and winds.
b. Unexpected flooding/water logging from nearby water bodies (before closure)
c. Leakage of pit lakes due to surface damage and land use
d. Hazards due to proximity of other industries

Internal Hazards:

a. Slopes failure of pit lakes.
b. Hazards due to external dumps maintained for the post mining period in case of large open cast mine having mineral: overburden ration as > 6.67.
c. Shrinkage of backfilled rock mass along the pit wall contact.
d. Subsidence.
e. Spontaneous combustion of coal leading to mine fires and AMD.

To deal with these hazards effectively, protective measures should be provided in the mine closure blue print made in the form of 'closure plan' and 'reclamation & rehabilitation plan'.

6. Industrial scenario

Internationally, pit lakes as self-sustaining aquatic ecosystems have been developed in the past in Europe, Australia, Africa and America but no official case record of pit lake development is available in Indian mining industry. Since, closure plan is introduced recently in India it is necessarily required to make the best use of the mined out pits in the form of pit lakes – to be developed by scientific reclamation. It should be noted here that in some abandoned mines, which are inundated or mine voids/pits were left unmanaged pit lakes are formed /developed without any planned effort. These 'unorganized pit lakes' can't be termed as pit lakes under discussions. As such water bodies are never investigated scientifically. Local people make use of these dug out excavations for miscellaneous purposes, e.g. bathing, fishing etc. But, if these are to be made into real pit lakes, 'Proactive Planning' and detailed case specific studies are needed. Hence, it is clear that research studies and technical information at the various levels (national and international) on the creation of pit lakes as an end use after mining are prudent for literature. In near future coal mines of Indian mining industry, which is aging with time, will certainly require such studies.

6.1. A case study for a coal mine of India

"Kerendari Mine Project" salient details of which are given in Table 2 form below has been approved to develop a water body as an end use of the mined out land [13]. The mine closure plan of this proposed mine project has been proposed to develop scientifically-planned mining pit lake after 30 years from now.

Table 2. "Kerendari Mine Project" salient details.

	Name of mine and location	**Kerendari BC open cast project (Karanpura Coalfield), Jharkhand, India** A captive mine for 3960 MW Tilaiya Ultra Mega Power Project (Under developing stage)
(a)	Company name	'Jharkhand Integrated Power Company Limited' (JIPL)
(b)	Pit lake dimensions (length x width)	800m x 700m (for West Pit)
(c)	Approximate pit lake area	560 hectare
(d)	Depth of pit lake (Ultimate)	45m
(e)	Mining pit depth	435 m
(f)	Planned pit lake shape	Irregular
(g)	Acid mine drainage /Acid rock drainage	Cannot be predicted as the mining operation is yet to start (if available, low to medium order only; conclusion drawn based on past records of study in other mines of the Karanpura Coalfield)
(h)	Water use (suggested at the time of mine closure)	Miscellaneous i.e. irrigational / industrial, pisiculture or agriculture purposes and not for drinking purpose
(i)	Pit lake envisaged to be available for use	after 30 years of the start of mining operation
(j)	Reclamation & Treatment	Needed; Backfilling required when created i.e. at the closure of mine and will depend on the end use of water.
(k)	Water Filling	Both naturally through rainwater accumulation, rainwater harvesting and by pumping from available nearby resources

This case study for 'pit lake development' (to be done in future) has been reported here with certain thoughts in author's mind, and especially for those companies or organizations in developing countries, which have to plan and start in the direction of pit lake development and they have no idea to start with. This review and theoretical knowledge will help them in formulation and conceptualization of their progressive ideas and arrive at a stage to start the execution work. Intentionally, no case report from published record about pit lake formation is added in the review because of site specific nature of mining and its end use. In its place a future planned case record of 'Kerandari Coal mine (India)' is briefly described. Thus, the review done by the authors is the 'representative overview' that can be utilized for practical evaluation, assessment and statuary compliance purposes.

7. Conclusions

Development of 'Pit Lake', as the end use of mine, is the best disposal system because such water ecosystem provides the most convenient and socially acceptable solution. It becomes further important, as water is a valuable commodity in the modern era, particularly for developing countries. In the days ahead, it is almost certain that such necessity and water uses (both) will be far greater than it is at present. Hence, it is beyond doubt that mining pit lakes, if developed, will provide great utility to the community. Providing proper maintenance and scientific management in a planned and scientific way, will make such artificially developed water bodies as socially acceptable.

Based on this review, it can be concluded that manipulation of pit lake chemistry is difficult, expensive, and takes many years to achieve remediation goals. For this reason, it is prudent to take steps throughout the mine operation to reduce the likelihood of future water quality problems upon mine closure. The scientific development of pit lakes as per mine closure plans will reduce the statute requirement as well.

Since pit lakes are best from ecological restoration view point, they are capable to compensate the damages caused due to mining. Similarly, they provide commercial benefits to the mining company owning it.

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دریاچه معدنی، به‌عنوان پایان استفاده از معدن‌کاری

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چکیده:

دریاچه‌های معدنی مانند دریاچه‌های طبیعی، از تنوع و گوناگونی‌های فراوانی برخوردارند. همچنین این مکان‌ها باعث عدم تعادل محیط اطرافشان می‌شوند و می‌توانند باعث نشست سطح زمین شده و کیفیت آب را نیز تحت تأثیر قرار دهند. در پایان عمر معدن و در مرحله غیرقابل استفاده بودن معدن باید بررسی‌های فنی از منظرهای گوناگون مانند آب‌های ایجادشده، ریخت‌شناسی، زمین‌شناسی، آب‌شناسی، کیفیت آب (ژئوشیمی) و زیست‌شناسی مورد مطالعه قرار گیرد. دریاچه‌های معدنی به‌عنوان منابع ارزشمندی برای مقاصد مختلف از قبیل سرگرمی و تفریح، ماهیگیری، تأمین آب و زیستگاه حیات‌وحش مطرح می‌باشند که البته بستگی به توپوگرافی منطقه، موقعیت آب مورد استفاده و مشخصات ایمنی دارد. دریاچه معدنی Alberta در کانادا، دریاچه معدنی Sleeper در Nevada ایالات‌متحده آمریکا و دریاچه معدنی Westfield در اسکاتلند مهم‌ترین دریاچه‌های معدنی هستند که در گذشته شکل گرفته‌اند. در صنعت معدن‌کاری در هندوستان تاکنون ایجاد دریاچه معدنی ثبت نشده است که علت آن این است که پس از پایان عملیات معدن‌کاری، هیچ‌گونه استفاده‌ای از معدن در پایان عمر آن صورت نمی‌گیرد. اخیراً، «طرح بستن معدن» با رویکرد استفاده علمی از آن در پایان عمر معدن در هندوستان مطرح شده است؛ یکی از این کارها در معدن زغال‌سنگ Kerendari در ایالت Jharkhand در هندوستان انجام شده است. به‌طور خلاصه، بعد از این فرصت بزرگ در طرح توسعه دریاچه معدنی، این قبیل تحقیقات و بررسی‌ها مخصوصاً برای کشورها و شرکت‌هایی که دارای معادن سطحی قدیمی هستند می‌تواند مفید باشد. مطالعه انجام‌شده در این تحقیق می‌تواند برای ارزیابی پروژه‌های پاک مورد استفاده قرار بگیرد.

کلمات کلیدی: دریاچه معدنی، معدن‌کاری، معدن‌کاری زغال‌سنگ، پایان استفاده از معدن‌کاری، طرح بستن معدن.