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PRINCIPLES OF ENVIRONMENTAL REMEDIATION IN OPEN AND CLOSED SYSTEMS: A CASE STUDY OF THE LAKE DIANCHI DRAINAGE BASIN

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ABSTRACT

The predominant links between systems science and environmental science are usually made by disciplines such as oceanography, climatology and ecology, but the relationship between systems science and environmental remediation, including contaminated soil and site remediation and solid and wastewater treatment, has not been fully examined. This paper therefore considers the principles of environmental remediation and waste treatment in the context of open and closed systems theory. The characteristics of these systems, to a large degree, dictate the types and parameters of possible interventions, particularly when operating at larger time and distance scales.

Three systems are discussed: closed systems, semi-open systems and fully open systems, providing an overview of system characteristics and behavior, along with examples of interventions commonly found in environmental remediation practice. The need for an integrated, interdisciplinary approach to environmental science, technology and engineering when effecting successful open system remediation is also highlighted.

A more detailed case study of these systems in the context of Lake Dianchi and its catchment system in Kunming is provided. Located in southern China, the Lake Dianchi drainage basin provides a valuable lesson in socially responsible, long-term environmental remediation, not only because it has been the focus of extensive local and international research and environmental remediation efforts since the 1990s, but because it provides credible evidence of the various types of systems described in this paper.

KEYWORDS: environmental remediation, open systems, closed systems, Lake Dianchi, drainage basin.

INTRODUCTION

In standard environmental theory, our earth is a closed system composed of a series of naturally open systems (White, et al., 1999). According to this model, the earth is a closed environmental system because it has a clearly delineated boundary (the upper atmosphere) and radiated energy (in this case, heat and light) is both an input to and output from the system; our so-called "biosphere" is described as "closed" despite its ability to exchange energy with its surroundings. Within this closed system there exist a variety of open systems (such as the atmospheric system, the lithospheric system, and the ecosystem), which have non-circumscribed boundaries and enjoy a constant flow of both energy and matter as inputs, throughputs and outputs, along with continual energy and matter exchanges with their surroundings. The transfer of energy and matter and the cascading of energy from subsystem to subsystem are fundamental concepts in these environmental systems.

While the definition of closed and open systems may vary somewhat between theorists and models, in each case the concept of a "system boundary" is indispensable; in closed systems the boundary is clearly defined and (mostly) impermeable except for well-regulated inputs and outputs, whereas in open systems the boundaries are obscure, vague and confusing, and inputs, throughputs and outputs may be exchanged with the surroundings in ways which are often unregulated and uncontrollable. As a consequence, all "environmental" systems (except the earth) are considered open systems and most (although not all) "industrial" or manmade systems are considered closed systems. [In this paper, the terms "closed system" and "open system" are not applied to environmental science in general but to the practices

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of environmental remediation, such as contaminated brownfield site remediation, and in-situ and ex-situ industrial and municipal waste treatment, and all forms of technological intervention have been conflated to "environmental remediation".]

When considering the range of possible systems encountered when remediating the environment, three basic types can be identified: 1) simple, closed systems; 2) more complex, semi-open systems; and 3) highly complex, fully open systems. Each system type lends itself to different interventions or a combination of interventions. [A fourth type of system, namely an "isolated system" in which there are no interactions across system boundaries, can also be distinguished in environmental science; however, this type is only encountered in the laboratory and is therefore not a subject of this paper. Similarly, specialist topics such as equilibrium and disequilibrium, equifinality, the Second Law of Thermodynamics and entropy, energy banks and sinks, and system variables and process cycles will be left for future discussion.]

In the context of environmental science, a closed system has a well-defined boundary, well-documented and well-understood inputs, clearly defined internal components and processes (in the language of industry, these are called "unit processes"), and (mostly) controlled outputs; in this sense, a closed system is described as "simple" because it generally does not share uncontrolled energy and matter with its surroundings (i.e., its "embedded environment") beyond essential inputs and outputs.

Semi-open systems also have well-defined boundaries, although these become more porous and harder to control as the system becomes environmentally and operationally more complex. Similarly, semi-open systems have a wider range of possible inputs; while some of these remain outside the control of operators most of them are understood and controllable or, at the very least, identifiable and documented. Semi-open systems also include well-documented internal processes and functions, but outputs are often less understood; being more unpredictable, they are also harder to control. In this sense, semi-open systems share many of the same traits as a closed system (and may even include a closed system, such as a waste treatment facility, within its sphere of authority), but also share some of the characteristics of a fully open system. For example, semi-open systems typically transfer controlled and some uncontrolled energy and matter to their surroundings.

The more complex, fully open system has an almost innumerable number and range of possible inputs; these are often almost beyond the range of human comprehension, and control of inputs is sometimes at the limit of, or even beyond, human understanding and ability. Moreover, the management of (and intervention in) such systems, particularly when they are contaminated with toxic substances or are unstable (i.e., in a state of "disequilibrium"), is extremely complex and requires specialist technical expertise and knowledge. The fact that open systems may also contain multiple sets of closed and semi-open systems, as well as other innumerable subsystems, within their boundaries makes for an even more complex arrangement of elements, internal processes and throughputs. Moreover, the boundaries of a fully open system may be uncircumscribed, porous and largely unidentifiable; the range and number of possible outputs from the system are (almost) countless, and may include long-term environmental and ecological impacts, many of which may be unknown or undetectable for decades into the future. As a consequence of this complexity, when considering intervening in these types of systems for the purposes of correcting environmental imbalance or treating contamination a "whole-of-system" interdisciplinary approach is required.

Each of these three systems can interact in straightforward as well as in heterogeneous ways; the output of one system can be the input to another system, and the subsystem of one system can be the input or output to another subsystem. Consider, for example, a typical dairy farm. The elements of a dairy farm include farmland (although some farms house cows year-round in sheds, which generate bedding manure, an output), feed, fresh water, cows, a milking shed (composed of tanks, shells and rubber liners, and water, an input), and so on. If we concentrate on the milking shed, a closed system, we can identify inputs (cows), controlled processes (rotary or herringbone milking machines arranged in parlours powered by an energy input using a pulsation chamber of atmospheric air, another input), and an output (milk, which can be an input to other industrial systems, such as cheese and skimmed milk production).

However, another output of a milking shed is solid and liquid waste. This waste, like all waste, can be viewed as an environmental problem to be overcome or as a resource opportunity to be utilized for further benefit, because dairy waste is rich in nitrogen (N). As such, this type of waste is useful as a fertilizer, either on the dairy farm itself or

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elsewhere, thus becoming an input to the nutrient supply and cycle of farms or agricultural land. Moreover, due to the presence of naturally occurring cellulose-decomposing bacteria and active digestive enzymes in dairy waste, milking shed waste may also be a valuable input into ex-situ composting facilities or combined with bedding manure for in-situ decomposition and reuse. Thus, the output of one system may be the input to another system. Such is the situation at Lake Dianchi.

The Lake Dianchi drainage basin consists of a 2,920 km2 catchment area in Kunming municipality, Yunnan Province (known as the "kingdom of non-ferrous metals") in southern China. At the center of the basin sits Lake Dianchi (the eighth largest lake in China), a 300 km2 freshwater lake containing 1.6 billion m3 of water with an average depth of 4.4 m; at 1,990 m above sea level, the name Dianchi means "a sparkling pearl embedded in a highland" (Fitzpatrick, 2010; Wu, et al., 2012). The Lake Dianchi drainage basin forms part of a larger catchment and drainage system associated with the Jinsha River, an upstream feed to the Yangtse River, the longest river in Asia and the third-longest river in the world, which flows for 6,300 km from the glaciers of Qinghai eastward through China into the East China Sea at the city of Shanghai. Within the Lake Dianchi drainage basin are a number of significant manmade and natural environmental systems, each of which contributes to the quality of water, sediment, soil and air in the catchment area. These include: 20 separate rivers systems, which flow into Lake Dianchi, and the Haikou River, the only natural river to flow out of the lake; an expanding urban population, which has grown from 1.5 million in 1980 to about 5.0 million today (Kunming City, with a population of almost 4.0 million, sits at the heart of the municipality); industries, many which are located in 30 industrial parks, including chemical and petrochemical production, phosphate mining and fertilizer manufacture, copper and other types of non-ferrous mining, like salt (Xiao, et al., 2007), magnesium, titanium and silica; and widespread agriculture and farming, including tobacco, rice and wheat (Ning, et al., 2013). For example, 14 different mineral ore reserves have been identified in the drainage basin, the largest of which is phosphate (PO4); there is a proven reserve of 1,477 million tonnes of PO4 with a total of 698 million tonnes having already been prospected. In parallel to these environmental inputs, there is also a fast-growing solar energy sector, a burgeoning organic food production fraternity (Dyer, 2012), and a more established flower-growing industry in Kunming.

However, in the last several decades these conditions have led to an unsustainable burden placed on the volume and quality of water entering and contained within Lake Dianchi (Liu, et al., 2015). According to Jin et al (2006, p. 159), the "drainage basin over the last few decades, combined with changes in land use, especially the lakeshore areas, has placed severe pressure on the lake. For example, the lake's once great biodiversity has been severely damaged. High levels of organic and nutrient loads to the lake have resulted in hypereutrophic conditions"; Jin (2003) has described the lake's hypereutrophic condition in detail. Moreover, where once the lake was dominated by macrophytes such as Ottelia acuminata (a member of the aquatic flowering plant family Hydrocharitaceae or tape grass), Potamogeton maackianus (an aquatic herb or pondweed) and Myriophyllum verticillatim (non-invasive whorled water milfoil) which covered 90% of the surface area of the lake, these have disappeared and been replaced by the invasive water hyacinth (Eichhornia crassipes, a native of the Amazon basin, introduced in the 1970s to phytoremediate phosphorus, nitrogen and heavy metals) and a phytoplankton microphyte biomass, dominated by blue-green algae, such as Microcystis aueruginosa and Aphanizmenon flos-aquae, both freshwater species of cyanobacteria (Jin, et al., 2006).
Similarly, the zooplankton biomass has increased dramatically with zooplankton per litre increasing from 1,800 individuals/L in the 1950s to 23,000 individuals/L by the 1990s; these include rotifer (so-called "wheel animals"), cladocera (water fleas) and copepod (fish parasites). However, during the same period the number of separate species has fallen by about 40% (Jin, et al., 2006). Furthermore, as a result of the disappearing macrophyte food source, 17 of the 24 indigenous fish present in the lake before the 1950s are now entirely extinct, and introduced exotic fish, such as the blue carp (Mylopharyngodon piceus), grass carp (Ctenopharyngodon idellus) and silver carp (Hypophthalmichithys molitrix), have become dominant. These environmental changes mirror urban, agricultural and industrial land use developments: in 1988, 19.6% of the drainage basin was unused land, however only 5.2% remained unused by 1999; and only 0.6% of the basin was used for garden plots in 1988, but 5.3% was used for this purpose in 1999 (Jin, et al., 2006; Wu & Feng, 2012).

This paper introduces the three types of systems cited above, discusses each in the context of principles of environmental remediation, and refers to the Lake Dianchi drainage basin as a case study in understanding how these systems present themselves in natural and manmade environments.

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CLOSED SYSTEMS

Features of the system

Systems theory provides an analytical framework for understanding the high-level organizing principles of elements and processes in manmade and natural systems, and shows the interdependence of elements within the system and the system's relationship to its surroundings; systems theory does not attempt to describe specific internal tasks or process engineering, but concerns itself with higher order integrating processes and interactions, and provides a holistic conceptualization of the working system. For closed systems, as shown in Figure 1 a), this framework is simple because manmade industrial systems do not "recognize" they are embedded in a wider environment. [In this and other diagrams, solid lines represent controlled inputs, throughputs and outputs, while dotted lines represent uncontrolled or "disorderly" inputs, throughputs and outputs; the term "throughput" in this context is used to mean all energy and information transfer within the system, not merely the rate of production or successful delivery of information, as in computer science.] In closed systems there is a demarcated system boundary (such as a building, physical plant or prescribed zone, such as a bunded area), a set number of identifiable inputs, throughputs and outputs, and the system (generally) does not interact with its surroundings; in short, the system is self-contained. Such systems have clearly detectable inputs, and these can be controlled, monitored, sampled, measured and adjusted in order to maintain a stable state; often, in-line monitoring and computerized feedback loops allow the system to self-correct, although these adaptive mechanisms are anthropogenic in origin and not natural.

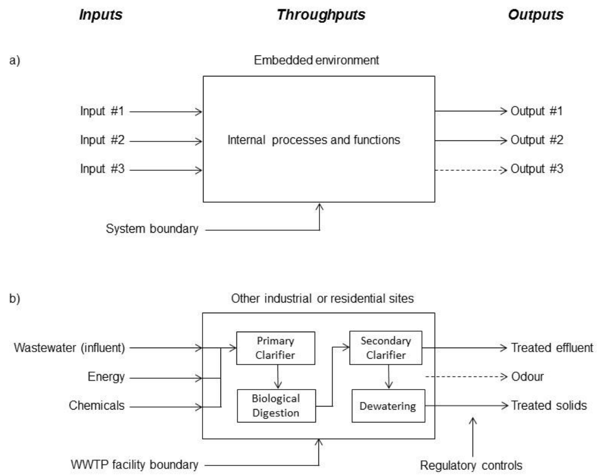

Figure 1: Generic overview of a simple, closed system a) and example of a closed-system industrial WWTP b), showing basic inputs, internal processes and functions, and outputs.

Similarly, there is a clearly identifiable set of internal processes with which operators can manage the system, allowing for relative ease in maintenance, risk management and incident response, health and safety assessments, and other standard procedures of operation and reporting. As a consequence, disallowing for unforeseen accidents and spills, and fugitive emissions and odors, outputs from the system are controllable and governed, usually by a regulatory body such as an environmental protection authority which oversees compliance. Such outputs must therefore conform to discharge (output) consents, thus necessitating tight controlling functionality within the system. Closed systems, while they can be expensive to capitalize, are generally less costly to manage than the semi-open or open systems discussed below.

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Figure 2: Photographic examples of closed systems: biodigestors at a sewerage treatment plant in Reading, United Kingdom (left); industrial wastewater bio-chemical treatment plant in Brisbane, Australia (right).

The following industrial examples qualify as closed systems: petrochemical plants, fertilizer plants, nuclear power plants, component manufacturers, alumina refineries, and aluminium smelters; in contrast to our biosphere, these systems form the "technosphere" and contribute to the world's so-called "industrial ecology". While clearly not all closed systems are "simple" (due to their complex design and sophisticated processes and throughputs) nor entirely "closed", their boundaries are prescribed, and their inputs and outputs are controlled, monitored and reported.

Figure 3: Photographic examples of closed systems: drum storage of contaminated industrial solid waste awaiting batch treatment in Tasmania, Australia (left); treating a batch of contaminated industrial soil within a bunded handling area in Melbourne, Australia, (right).

A variety of closed subsystems related to environmental remediation may be embedded within these types of systems, including industrial wastewater treatment plants (WWTPs). Figure 1 b) introduces the basic inputs, internal processes, outputs and system boundary for a typical WWTP (Figure 2, right). Primary inputs are wastewater, energy and chemicals; basic processes are primary clarification, biological digestion, secondary clarification and dewatering; outputs are treated effluent (which is generally discharged to the sewer from the secondary clarifier and subsequently treated by a downstream sewerage treatment plant [STP], another closed system) and treated filter cakes or other dewatered solids (which are transported off-site to landfill, yet another system); an unwanted output may be objectionable odour (which mixes with and disperses to atmospheric oxygen). The system's boundary is clearly demarcated, and outputs are controlled and monitored; such systems are often designed and operated to meet specific discharge criteria.

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Another common example of environmental intervention, which is itself a closed system, is the municipal STP; these types of intervention may use simple trickling filtration or activated sludge methods, or may employ the more sophisticated biological nutrient removal (BNR) method (Figure 2, left). Other closed-system examples of environmental remediation include batch treatments of contaminated industrial solids (Figure 3, left), batch chemical treatments, batch treatments of biosolids, and batch treatments of contaminated industrial soil (so called "technosols", Figure 3, right), which use *in-situ* interventions, such as in-situ chemical oxidation (ISCO) or *ex-situ* immobilization, bioremediation, natural attenuation or bio-stimulation processes.

Example of Lake Dianchi Drainage Basin

In the Lake Dianchi drainage basin there are 777 industrial enterprises with pollutant discharge licenses, many of them phosphate and fertilizer manufacturers (presumably, these enterprises have some type of waste treatment capability or intervention embedded within the system, because Jin *et al.* [2006] report that all industrial polluters in the basin "basically comply" with discharge standards), eight secondary STPs built between 1988 and 2001 with a treatment capacity of nearly 600,000 m^3/day (the dry season treated sewage percentage increased from 60% in 2000 to 80% in 2004), and an interception canal at the north bank of the lake designed to intercept 300,000 m^3/day of polluted river water before it enters the lake from urban areas. The No. 1 Kunming STP is a standout in this context, treating 150,000 m^3 of sewage per day and generating 45,000 m^3 of clean water per day at a standard exceeding the national benchmark.

However, Medilanski *et al.* (2006) have questioned the wisdom of applying the centralized urban wastewater treatment model to the Lake Dianchi drainage basin in order to reduce nutrient loads entering the lake; they note while STPs may have an installed capacity of 600,000 m^3/day of phosphorus- (P) and nitrogen- (N) rich urban wastewater, only about 25% of the wastewater actually reaches the STPs, and non-point source agricultural and industrial runoff may be the source of much higher concentrations of P and N entering the lake (Gao, *et al.* [2015] also make this point). Thus, Medilanski *et al.* raise an important point about the relationship between a system (assuming in the context of this paper such systems have a contamination problem) and the environmental remediation methods used to correct it: if the system is "closed" the polluting effects of the system are largely controllable; however if the system is "open", as we will discover is the case with Lake Dianchi, then using simple, closed-system methods to address open-system complexity may be inappropriate or inadequate, or both. While this argument does not negate the need for closed-system environmental approaches, it begins to widen the discussion to consider higher order factors and the need for interdisciplinary approaches to tackle the intractable consequences of pollution within the system.

Nevertheless, Jin *et al.* (2006) cite a number of continuing centralized projects which can be identified as closed systems within the basin, including commissioning the western suburban sewer system in Kunming City, an upgrade and extension to the No. 1 Kunming STP and sewers to 120,000 m^3/day of clean water, finalizing the eastern (50,000 m^3/day) and northern (75,000 m^3/day) STPs and sewers, and completing the so-called Chenggong (15,000 m^3/day) and Jinning (15,000 m^3/day) "small village" STPs and sewers. Harder to find are data on the status, performance standard and output of industrial WWTPs, farms and agricultural runoff and mine site runoff within the drainage basin, leaving the possibly open that Medilanski's assertions may be right.

SEMI-OPEN SYSTEMS

Features of the system

As discussed above, semi-open environmental systems share traits with both closed and open systems. However, the distinction between semi- and fully open systems is not an academic one: semi-open systems are much harder and more costly to manage than most closed systems because their boundaries are more porous and interactions with their surroundings are more numerous, complex and harder to control via effective environmental remediation. For example, consider Figure 4 a). Of note in this generic model are identifiable and controllable inputs along with the introduction of unidentifiable and uncontrollable inputs. These may be "natural" in origin or the product of anthropogenic activities near the system, and may include large volumes and diverse types of inputs; in both cases, impacts on the system may be hard to control, manage and financially project. More porous system boundaries may also result in greater interaction between system and surroundings, and these too may be hard to control, posing new risks to the integrity of the system, including the introduction of foreign contaminants, unintended health and safety risks, and uncertainty. Assessment of risks also becomes more challenging due to the presence of innumerable and uncontrollable interactions between system and surroundings.

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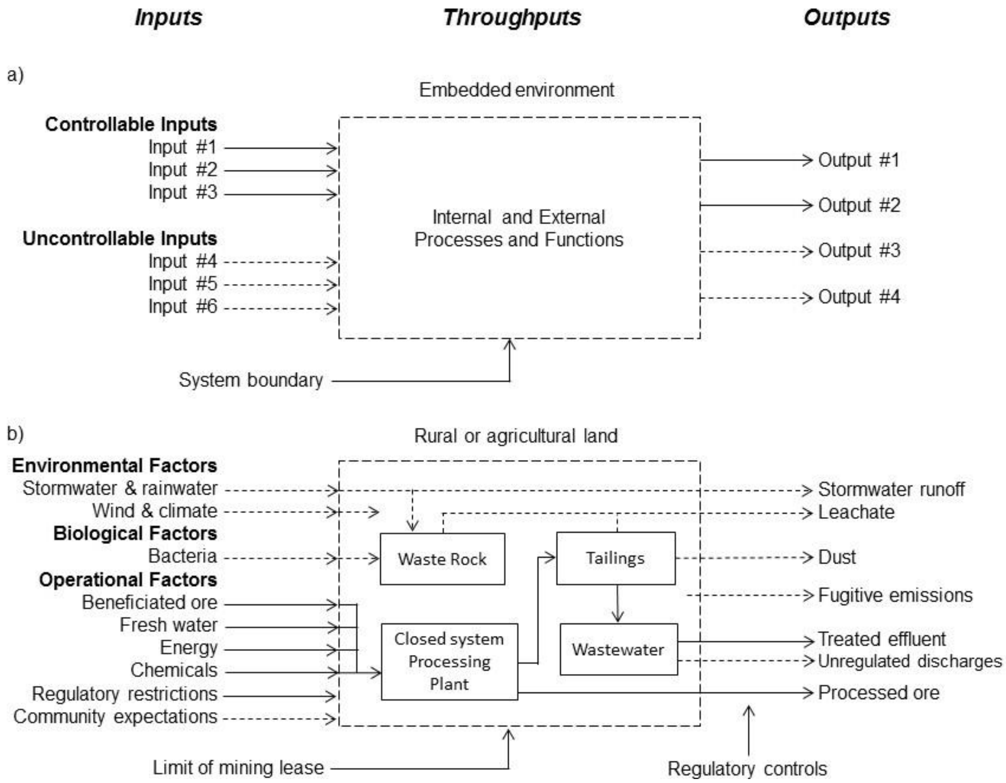

Figure 4: Generic overview of a semi-open system a), and example of a semi-open operating mine site b) showing inputs, internal processes and functions, and outputs.

Given the porous nature of semi-open system boundaries, closed-system waste treatment processes and other internal functions may be compromised or complicated, making not only management, but monitoring and reporting, more problematic. Such circumstances may result in uncontrolled and unscheduled discharges to the environment. However, as in closed systems, internal functions like sampling are still relatively easy, and the boundaries and internal processes of the system are prescribed; meeting regulatory limits and operating parameters, while more challenging, are still manageable. As a consequence, reporting requirements are generally more stringent than with closed systems, and standards of reporting become the domain of environmental scientists rather than industrial technologists.

Examples of semi-open environmental systems include, operating mine sites, which contain open cut pits, tailings dams and waste rock dumps (Figure 5, right), contaminated industrial sites (referred to as “brownfield” sites, often located in urban or residential neighborhoods, Figure 6, right), urban drainage canals and channels which may carry human and industrial effluent in addition to stormwater (Figure 5, left), composting facilities (Figure 6, left), farms, landfills and other refuse dumps.

An operating mine site is an embodiment of a semi-open system because it has closed system attributes, such as controlled, operational inputs, a demarcated processing plant and a clearly specified lease boundary, but also behaves like an open system because of the many energy and material transfers which may occur with its natural surroundings. Figure 4 b) presents an example of a semi-open operating mine system. Inputs have been expanded to include uncontrollable environmental factors, such as rain events, wind, climatic changes, and bacteria (such as *Thiobacillus ferrooxidans* and *Thiobacillus thiooxidans*, which are common on mine sites, or in the case of the Lake Dianchi drainage basin *Sulfobacillus Thermosulfidooxidans*); the latter are hidden but active participants in chemical processes and waste degradation at mine sites.

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Figure 5: Photographic examples of semi-open systems: open stormwater and municipal waste canal in Orihuela, Spain (left); open cut mine pit and pit water at an operating metalliferous mine site in Tasmania, Australia (right).

Subsystems within the semi-open mine system are waste rock dumps, which foster their own micro-ecologies, and tailings dams, which encourage unique chemical reactions, often in anoxic or anoxic-reducing conditions; other semi-closed subsystems within the larger operating mine system include open cut pits (which fill with rainwater containing bacteria), dams, lakes, ponds and drainage galleries, all of which have narrowly prescribed boundaries (these can be as simple as bunds or other means of containment, like gallery walls and reactive barriers) but interact with their natural and anthropogenic surroundings by sharing energy and matter. Outputs from the system are a combination of controlled and uncontrolled processes, including the primary commercial output of a mine site: processed ore.

Environmental remediation of semi-open systems becomes more expensive, takes longer and is generally more complicated that remediation associated with closed systems. For example, it is far more costly and complicated to treat a waste rock dump than a batch of contaminated industrial soil. Mine site interventions include permeable reactive barriers (PRBs), stormwater and leachate interception drains and reactive drainage galleries, direct addition of chemical reagents to neutralize acidity and bind heavy metals, permeable and semi-permeable capping and revegetation, odour monitors and controls, and dust suppression, among other approaches.

Figure 6: Photographic examples of semi-open systems: composting facility at a dairy farm in Saudi Arabia (left); disused and contaminated industrial site in Melbourne, Australia (right).

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Example of Lake Dianchi Drainage Basin

There is a significant number of semi-open systems within the Lake Dianchi drainage basin, and steps have been taken to regulate their discharge to the local environment and to the lake system. Perhaps the most obvious semi-open systems in the drainage basin are its PO_4 mines (along with their commensurate closed-system fertilizer plants), although urban canals, agricultural ditches (Xu, *et al.*, 2006), farms, landfills (such as the Wuhua municipal sanitary landfill to the north of Kunming City, one of two with a gas-to-energy capacity in Kunming), and the Xiyuan tunnel (an artificial outlet of the lake) also qualify. Planned interception channels, such as the Cailian River diversion, the interceptor along the upper stream of the Panlong River, and the interceptor along the western bank of Lake Dianchi (Jin, *et al.*, 2006), have been proposed and may also qualify for further study within the framework of this semi-open model.

As noted above, among non-ferrous metals in Kunming, the primary one mined and processed is PO_4, the beneficiation of which is explained by Li (2012). Some of the phosphate-derived chemicals manufactured in the Lake Dianchi drainage basin include sodium aluminium hydrogen phosphate ($Na_3Al_2H_{15}[PO4]_8$), phosphorus pentasulfide (PS_5), calcium dihydrogenphoshate ($CaH_4O_8P_2$) and calcium phosphate ($Ca_3O_8P_2$), although the scope of undoubtedly important impacts to the lake from these chemicals is unclear. However, Yang *et al.* (2014) have documented the general aftereffects of PO_4 mining in Kunming, explaining the causes of ecological damage in the drainage basin are primarily due to the destruction of native vegetation as a consequence of removing overburden and the extensive land required for dumped spoil, and Jin *et al.* (2006) have highlighted the need for tighter restrictions on PO_4 mining. These, along with other sources of P and N in the drainage basin, including fertiliser plants (Gao, *et al.*, 2015a, 2015b), are the primary causes of hypereutrophication and the historically declining water quality in Lake Dianchi (Wang, *et al.*, 2014), but their partial or complete remediation to date have yet to be fully documented.

OPEN SYSTEMS

Features of the system

Use of the term "open system" is often applied to complex atmospheric systems, specifically in relation to the flow of air (White, *et al.*, 1999); examples of these systems can be found in contemporary computational models which map greenhouse gas emissions and global climate change. The causes of open system complexity are numerous and system behavior can be subtle, but generally include the following. In an open system, the parts of the system are interrelated and the overall "health" of the system is contingent on balanced subsystem functioning. As cited above, open systems are complex because they import and export energy and matter to and from their surroundings across system boundaries, and materials pass easily from and to the system due its permeable and ill-defined boundaries. Some open systems even have the capacity to regulate boundary permeability and thereby control the flow of "goods and services" to and from system and subsystem.

Figure 7: Photographic examples of open systems: abandoned lead mine, smelter and "tailings beach" in Baia de Portmán, Spain (left); abandoned quarry pit lake, Queensland, Australia (right).

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Furthermore, complex open systems consist of many interrelated subsystems which convert inputs into outputs through internal processing. These can be described as: “production” subsystems, which carry out transformation and production; “supportive” subsystems, which ensure inputs are available to production; “maintenance” subsystems, which uphold homeostasis or balance in the system; “adaptive” subsystems, which monitor the surroundings and generate appropriate responses to them; and “managerial” subsystems, which coordinate, adjust, control and direct subsystem behavior. As such, open systems, particularly open environmental systems, are sometimes referred to as “super-systems”.

Examples of open systems encountered when remediating the environment include unimpeded stretches of contaminated land, lakes, rivers and creeks, abandoned processing plants (Figure 7, left), abandoned quarry sites (Figure 7, right), disused mine sites (Figure 8, left and right), tailings “beaches” consisting of accumulated solid mine waste, and mine waste dump sites; in the context of this paper, open systems also include drainage basins or catchment areas, and often refer to interactions of unintended polluting effects and environmental counteractions between systems.

[In contrast to the semi-open operating mine system, which is monitored and managed as part of a mining operations plan (MOP), abandoned and derelict mines are classified as “open” because they have been left to the elements and, over time, merge with larger and more dynamic surrounding environmental systems; moreover, natural attenuating forces on contaminants can take decades, or even thousands of years in the case of tailings at abandoned uranium mines, to materialize.]

Figure 8: Photographic examples of open systems: contaminated river system at an abandoned iron ore mine in Tasmania, Australia (left); a series of derelict lead mines dating from the first century AD to 1990s in Muricia, Spain (right).

For this reason, open systems in environmental remediation should always be conceived in the context of their interdisciplinarity, in their “whole-of-system” context, and often require advanced systems engineering when sustainable outcomes are sought. In addition to process engineering and design, interventions may require the expertise of ecologists, geologists, environmental chemists, geo-environmental scientists, soil scientists, hydrologists, and agronomist engineers, among others. Such an integrated systems’ framework, which includes cross-platform and cross-infrastructure thinking, in the context of social-ecological-infrastructural systems and the management of sustainable cities has been well explained by Ramaswami *et al.* (2012); they maintain that such an approach mitigates environmental pollution and risks to human health, and the approach has been advanced to avoid the “silo effect” when approaching complex environmental remediation.

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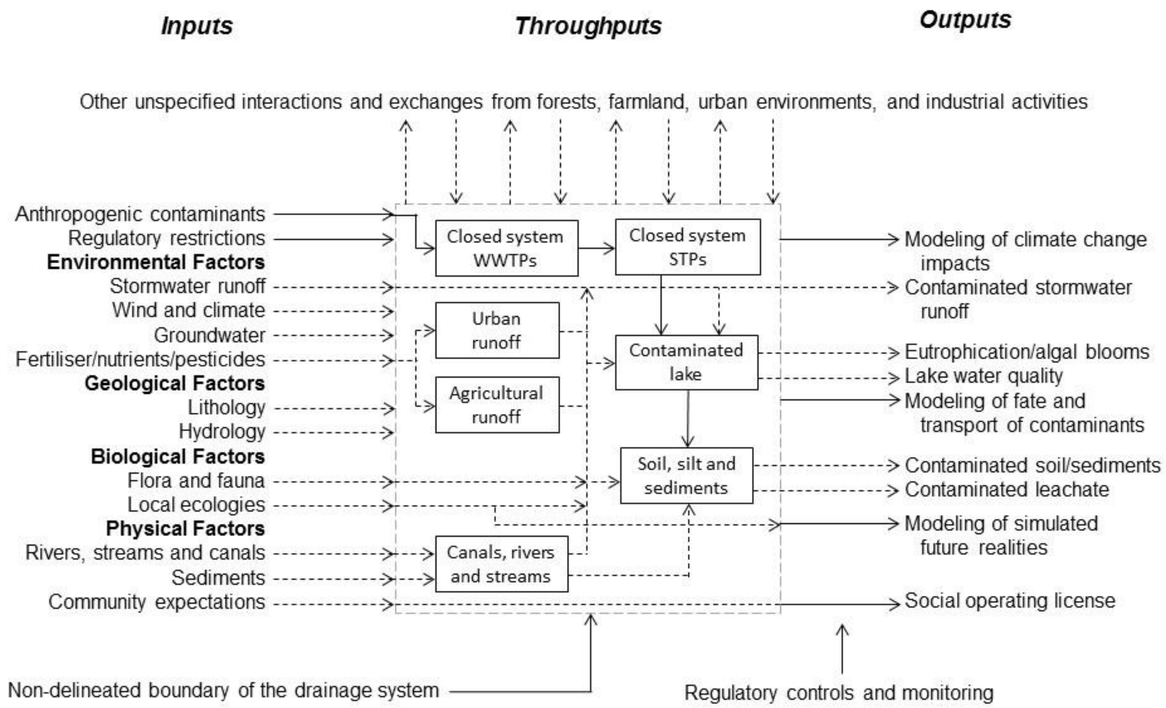

Figure 9: Overview of a fully open environmental lake system showing inputs, throughputs and outputs.

Figure 9 presents the open-system model in relation to a lake and drainage system. Of note is the introduction of controllable, as well as many more uncontrollable, inputs. These include environmental factors such as stormwater and wind, geological factors such as lithology and hydrology, biological factors such as flora and fauna and the role of local ecologies in shaping the behavior of the system, and physical factors such as river and stream dynamics, many of which transport contaminated sediments and silts, along with controllable factors like anthropogenic pollutants from industrial and municipal waste. In parallel to these are controllable inputs like regulatory restrictions (such as guidelines and standards), as well as uncontrollable inputs like community expectations and the collective will of local inhabitants, which may or may not result in desired or predictable outcomes, such as a social license to operate. Of note also are the multiple unprescribed, spontaneous interactions which occur between system and subsystem and between system and surroundings; in the case of Lake Dianchi, surroundings include not only forests but also agricultural and industrial systems, some of which may have long-term polluting consequences for the health of the lake and its environment.

Challenges associated with modeling open systems have been discussed in the context of equifinality and the generalized likelihood uncertainty estimation (GLUE) methodology (Bevan & Freer, 2001); hardships associated with modeling indeterminate open systems, while difficult, can result in a better understanding of a number of issues, such as climate change impacts on and from the system, the fate and transport of contaminants within and through the system, and ultimately the possible future condition of the system when adjusting variables such as the role of local ecosystems and changes to inputs like rivers, urban waste and anthropogenic pollution. However, as will be seen in the Lake Dianchi example, these come at a cost, a cost which can be non-trivial in the context of open system environmental remediation.

Example of Lake Dianchi Drainage Basin

Rather than model the Lake Dianchi drainage basin using the simple input, throughput and output model, Figure 10 shows the interactions between causes and effects of environmental degradation in the lake (the primary source of fresh water for Kunming City) and the wider basin, with a focus on population and industrial growth (input) and decreased biodiversity (consequence). For example, the diagram shows that with increased population (a) and industrial activity (b), and thus greater urbanization (c), pressure is placed on supplies of land, water and food (d) while at the same time polluting water and increasing siltation in the lake (e). Increased pressure on the land and water

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means greater soil erosion due to more mining, agriculture and deforestation (g) along with the use of more agrichemicals (i), such as superphosphate (containing P) and urea (containing N), both of which are contributors to declining water quality in the lake (e).
At the same time, the value of land increases, resulting in greater pressure to reclaim land (f); however, foreshore reclamation initiatives result in greater flood hazards (h) and the destruction of littoral zones around the lake (j) leading to the aforementioned decline in endemic macrophyte communities (k). As discussed above, this has led to both the rise of exotic fish species in the lake (l) and the significant loss of endemic fish species (m). Both the increase in water pollution, specifically the rise of a microphyte algal biomass (examples of which can be seen in Figure 11), and the loss of indigenous fish have led to a pronounced decrease in biodiversity (n) in the Lake Dianchi drainage basin. As a consequence, the effective, socially responsible and sustainable remediation of the Lake Dianchi drainage basin has become a topic of national importance and a focus for environmental science (Liu, *et al.*, 2015).

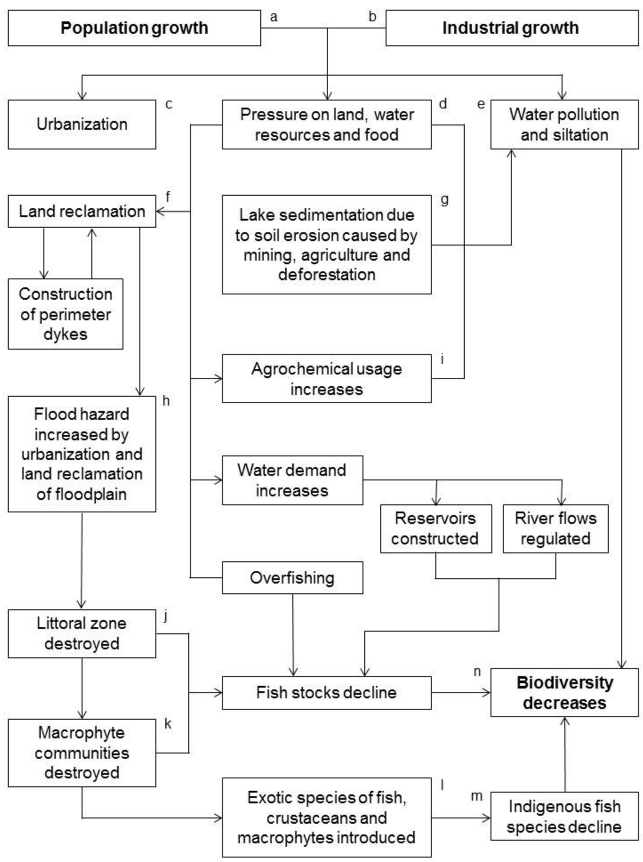

Figure 10: Causes and effects of degradation in Lake Dianchi and its drainage basin (Source: Jin, Wang and He, 2006, p. 175).

For this reason, a number of remediation efforts have been implemented (Li, *et al.*, 2012). For example, He and An (2001) and Lui *et al.* (2015) suggest the history of pollution control and ecological restoration in the Lake Dianchi drainage basin can be divided into three phases: the preliminary examination phase from the late 1980s to 2000 during which laws, regulations, policies, plans and systems of environmental protection were developed and implemented; the so-called "difficulty tackling stage" from 2001-2010 during which pollution controls, such as the installation of new STPs and WWTPs, increased considerably and the deteriorating trend of water quality was reversed (this phase was accompanied by a surge in published research on the lake and basin); and the "preliminary achievement stage" since 2011, during which the primary task of environmental scientists and systems engineers was to explore new ways of combining pollution control and protection along with development of the Lake Dianchi drainage basin.

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Details of these phases can be summed up by the so-called "2258" project in 1997, which was impelled by declining water quality in the lake and resulted in the expenditure of an initial $28 million to channel 50 m^3 of unpolluted water from the Songhuaba Reservoir to supply clean drinking water to 800,000 people living in suburban Kunming City; this initiative resulted in a 50% decreased drinking water demand being place on the lake. Then in the late 1990s, the World Bank co-financed the seven-year Yunnan Environment Project (YEP) at a cost of about $242 million. The YEP framework focused on "providing a sustainable environmental framework for the longer-term economic and social development of the Province, while providing a foundation for competitive industrial growth" (Jin *et al.*, 2006, p. 170). Thus, the project placed emphasis on improving catchment management by controlling both point and non-point sources of pollution, including the design, installation and commissioning of drinking water and wastewater infrastructure and the provision for solid waste management. This project was conducted in parallel with the so-called "Zero O'clock Action" of 1999, which identified that industrial pollution must be stopped immediately (Zhang, *et al.*, 2014).

In parallel to YEP, the central government developed its own framework to begin remediating the drainage basin, investing nearly $1.0 billion in 26 projects between 2001 and 2005, with an emphasis on "pollution control [with an aim of reducing the total pollution load to the lake by 20%], ecological restoration, optimization of resources allocation, supervisory management and scientific demonstration" (Jin *et al.*, 2006, p. 169). However, in accordance with the aforementioned characteristics of open-system modeling, the authors concluded "it is difficult to observe the effects of management actions [to the lake] over the short term", although they have modeled the load of P in Lake Dianchi from the 1950s through to 2020 and shown the relationship between doing nothing and the projected beneficial results expected from YEP.

As can be seen in Figure 10, reducing pollution loads and restoring the ecological health of the drainage basin are related. These efforts have been summarized by Lu (1998), Li *et al.* (2010), Li *et al.* (2012), and Lu *et al.* (2013). For example, Wu *et al.* (2012) found evidence of polybrominated diphenyl ethers (PBDEs) and their isomer decabromodiphenylethane in Lake Dianchi sediments (the highest recorded level in 12 contaminated Chinese lakes). PBDEs, for which there are 209 possible variation compounds, are fire retardants used in products like building materials, furnishings and motor vehicles. While the precise sources, modes of transport and fate of PBDEs in Lake Dianchi have not been identified, their presence is worrying given that PBDEs are intractable and do not readily attenuate naturally, can bioaccumulate in blood, breast milk and fat tissues, have been found in foodstuffs like salmon and beef and in sewage sludge and wastewater, and have hormone-disrupting effects in humans. Wan *et al.* (2011) similarly found evidence of polychlorinated biphenyls (PCBs) in Lake Dianchi water (up to 72 ng/L) and sediment surfaces (up to 2.4 ng/g), although not in lake sediments *per se* (the sources and fate of PCBs in Lake Dianchi are also unknown); Duan *et al.* (1999) had earlier found evidence of genotoxicity from industrial effluent and farm runoff in 12 dry season and wet season soil samples around the edge of Lake Dianchi, although this may have disappeared due to remedial actions taken during the "Zero O'clock Action".

However, as noted above, by far the greatest need for pollution control in the lake has been for contaminants associated with hypereutrophication, namely P and N. One of the challenges in Lake Dianchi is the phenomenon of so-called lake "back flow", which is due to the prevailing winds in the basin moving in the opposite direction to natural water flow, making the removal of pollutants, such as algae, more difficult (Liu, 2015). Wang *et al.* (2009), studied the historical presence of both P and N in Lake Dianchi sediments and found a distinct increase of both since the late 1970s, and An and Li (2002) investigated the relationship between lake water quality and sediments.

An and Li (2002), Gustavson *et al.* (2008), and Hu *et al.* (2010) have examined the effectiveness of dredging lake sediments in order to remove P- and N-contamination from the lake bed. For example, Hu *et al.* (2010) analyzed water quality, sediment and aquatic organisms before and after a dredging project. Results indicated that dredging efforts removed more than 1,700 tonnes of P and 20,000 tonnes of N, thereby reducing total P from 8.1 mg/L to 0.7 mg/L and total N from 8.9 mg/L to 1.0 mg/L in the water column. These nutrient decreases resulted in an increase in water transparency of 0.37 m to 0.8 m, and these improved underwater light conditions provided the mechanism for an aquatic ecosystem recovery trend.

Magistad (2011) has also reported on changes in local farming practices, such as one 100 acre hydroponic farm growing 30 different types of vegetables with only sewage as a nutrient source but no contaminating outputs, and

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similar trends have been observed in revegetation efforts at abandoned phosphate mines. For example, Yang *et al.* (2014) studied the environmental impacts of PO_4 mining in Haikou, which caused desertification, loss of biodiversity, and the potential for landslides and ground erosion. As a result of these efforts, Yang *et al.* report their "new mode of mining reclamation" has economic, environmental and social value, including the prevention and control of landslides using cut and fill technology, improved drainage, safety net protection, retaining wall construction, and vegetation cover by recruiting native plant species.

However, despite these considerable efforts, further environmental remediation is required, and the various interventions deployed so far have only partially resulted in the "clean up" of Lake Dianchi. For example, based a survey of published research it is obvious that further work is required to understand the current conditions of, and a modeled future for, groundwater in the Lake Dianchi drainage basin; although Huang *et al.* [2014] have begun this process. There is no doubt, however, that a significant amount of valuable and socially responsible environmental remediation on all types of systems within the drainage basin has already occurred, much of it conducted using interdisciplinary methods. Nevertheless, Jin *et al.* (2006) have identified several "lessons learned" from remediation efforts carried out between 1999 and 2005, including the lack of a harmonized sustainable development strategy, insufficient awareness of the long-term and arduous nature of this "complicated task", and insufficient awareness of the ecological fragility of the drainage basin.

CONCLUSION

From this brief overview of systems science and its relation to the principles of environmental remediation, it should be clear that prior to any sustained environmental intervention or initiative there is a need to know what type of system is being impacted, what the inputs, throughputs and outputs of that system are likely to be, what interactions between system and subsystem and between system and surroundings might occur, and what other possible outcomes from the intervention could eventuate (i.e., in addition to the intended ones). In this sense, systems science contributes not only to a holistic view of the system but also helps identify the appropriate intervention strategy, necessary expertise needed for the job, and types and scope of interdisciplinarity required to positively influence contaminants in or polluting influences on the system in question. This merging and working together of technology, know-how and expertise are the cornerstones of socially responsible environmental practice; such a conclusion has also been advanced by Jin et al. (2006) and Ramaswami et al. (2012).

Moreover, in complex open systems an extensive and coordinated series of closed-system interventions may not be sufficient when considering environmental factors related to semi-open and open-system intervention solutions. Interdisciplinary methods utilizing programmatic designs and a "whole-of-system" approach, which consider interactions between interventions and investigate how these interventions might affect technological as well as ecological processes across the entire system, are required. Such approaches to remediation not only represent best environmental practice but expand concern for the commercial, technical and academic aspects of remediation to embrace solutions which directly affect (and hopefully enhance) the quality of lives and livelihoods of people living in and around such dynamic environmental systems.

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