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TECHNICAL COMMUNICATION

Holistic Design of Wetlands for Mine Water Treatment and Biodiversity: A Case Study

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Abstract

Passive treatment wetlands are conventionally designed with the primary objective of purifying contaminated mine water; any benefit of enhanced biodiversity is ancillary. We propose a new approach that incorporates enhanced biodiversity as an explicit objective. In this approach, treatment units are selected based on water flows and chemistry and the ecological requirements of key species are identified. Elements of the wetland design that meet these distinct requirements are selected and sized, then merged within the constraints imposed by site geomorphology and hydrology. This concept is illustrated with the wetland design for the Los Bronces Mine in Chile, where aspects of treatment, biodiversity, and water management were developed separately, and then integrated into a holistic design. The treatment wetlands are integrated within the local ecology. This approach adheres more closely to the objective of designing wetlands that offer ecosystem services and also meets the requirements for long-term water treatment.

Keywords Ecological engineering · Treatment wetlands · Nature-based solutions · Mine drainage · Biodiversity

Introduction

The recent popularity of using nature-based solutions for engineered processes or structures has brought new interest in designing wetlands that treat water, enhance biodiversity, control erosion and regulate water flows (Nesshöver et al. 2017; The Source 2020). It is well established that natural wetlands can treat contaminated water, such as mine drainage, yet still support a healthy biota (Sobolewski 1997, 1999). Even natural wetlands that receive large flows of contaminated water from operating mines can function as normal, healthy ecosystems (e.g. Bishay and Kadlec 2005; Hambley 1996; Sobolewski 1997). Thus, it should be possible to design a wetland that detoxifies contaminated water and harbours a healthy flora and fauna.

The description of ecosystem services provided by wetlands is relatively straightforward but designing them to provide diverse services is more complicated. Design for treatment purposes follows strict engineering rules for wastewater treatment (Dotro et al. 2017; Langergraber et al. 2020), whereas designs that promote biodiversity is largely guided by rules-of-thumb (Hansson et al. 2005; Oil Sands Wetlands Working Group 2000). Often biodiversity design goals lack focus, clear criteria for success, or thorough implementation (Benyamine et al. 2004; Hansson et al. 2005; Wiegleb et al. 2017). Designing wetlands to regulate water flow is understood even less.

In 2018, Anglo American contacted us to develop a wetland that would treat contaminated mine water, enhance biodiversity, and attenuate flows. The wetland will be sited in a 20–30 ha area associated with the Perez Caldera dam, after the company removes flooded tailings currently stored behind the dam. This area drains the mine site and receives surface runoff and groundwater originating from mountains within this watershed.

As practitioners in the field, many of us know how to design wetlands that treat mine drainage, but not wetlands that provide all the ecosystem services requested by Anglo American. The conventional approach to the design of treatment wetlands draws from the discipline of wastewater engineering (Dotro et al. 2017; Langergraber et al. 2020). The design is focussed on matching influent characteristics to the treatment processes for contaminant removal, sizing a system based on contaminant removal rates, and establishing design specifications within an excavated bed. This approach

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was first established in 1994 for treatment of contaminated coal mine drainage by the U. S. Bureau of Mines (USBM) (Hedin et al. 1994; Skousen et al. 2017). None of the above documents offer guidance on the provision of other ecosystem services, such as enhancement of biodiversity, protection against shoreline erosion, or management of water flows.

Design elements that enhance biodiversity have been described for a variety of applications (Hansson et al. 2005; Oil Sands Wetlands Working Group 2000; Benayas et al. 2009), including for the design of treatment wetlands (Kadlec and Wallace 2009), but biodiversity is still considered an ancillary benefit in these systems. The relationship between design criteria and increased biodiversity is qualitative and measures of success are ill-defined. This contrasts with the requirements for the design of treatment wetlands, which must comply with strictly-defined discharge criteria. This paper presents an approach to the design of treatment wetlands that provide multiple ecosystem services. This approach was developed within the context of treating the drainage from the Los Bronces Mine. This approach, though unconventional, was ecologically-sound.

Results and Discussion

The design of a wetland at the Los Bronces Mine is severely constrained by the circumstances at the site. The mine is located at 3500 m above sea level in the high Andes, 65 km from Santiago, Chile. At this elevation, most of the mine is above the tree line, with sparse vegetation predominantly established along the valley bottom, which drains runoff and groundwater from the mountains surrounding the site.

The site ecology is constrained by a limited growing season, limited precipitation, limited nutrients, and poor soil development. The main source of water is from snowmelt during the spring. Thus, both flora and fauna at the site are sparse: ecological surveys at the site identified a total of 70 plants species and 114 resident and transient animal species (Biota 2017a, b). Birds are the predominant fauna in this region, with 80 species identified during annual surveys, though there are only three resident species at the mine site. Altogether, there are only 15 animal species endemic to the area. In this context, enhancing biodiversity is challenging, and it is difficult to see how "increasing shoreline complexity" would make much difference with the flora and fauna in this environment.

We felt that these circumstances demanded a different process to design a wetland providing the desired ecosystem services. To that end, we: (1) identified water treatment requirements; (2) identified requirements for a healthy wetland ecosystem; (3) identified requirements for water storage and supply, and (4) developed a wetland design that integrates these different requirements.

Table 1 Processes considered for treatment of mine drainage at Los Bronces Mine

Contaminant	Treatment process
pH	Limestone neutralization
Cu	Adsorption onto organic matter; Sulphide precipitation
Mn	Oxidation into insoluble MnO_2 (pyrolusite)
Trace metals	Adsorption onto organic matter; Adsorption onto manganese dioxide

These requirements will be bounded by the characteristics of the water feeding the wetland, as well as the climactic and geomorphic constraints of the site. To design a wetland that treats mine water, influent chemistry is matched to treatment processes to identify treatment units, size them, and develop a preliminary, conceptual design. However, mine water at Los Bronces was incompletely characterized at the time of this study. Therefore, only a general, conceptual design could be derived, based on available knowledge of mine water characteristics.

The water at Los Bronces is known to be acidic and contained elevated copper, manganese, and trace metals. The processes required for passive treatment of such water are summarized in Table 1.

Design criteria for limestone channels or drains to neutralize acidic pH are published (Hedin et al. 1994; Skousen et al. 2017) and we have in-house design criteria for copper and manganese removal (Casino Mining 2013). These and other resources were used to size and design treatment units that embody the processes listed in Table 1 and allowed us to elaborate a conceptual design for water treatment.

There is a logical sequence to the order of these processes. Water must first be neutralized to meet the circumneutral requirement of other treatment processes. Second, the bulk of toxic metals can be removed under anaerobic conditions in deep, subsurface flow organic beds. There, concentrations of the predominant contaminant, copper, would be decreased to sub-ppm concentrations through adsorption and formation of insoluble sulphides (Sobolewski 1999). Most other contaminants of concern will also be removed, except for iron and manganese. Thus, most of the potentially toxic elements in mine water would be removed in an environment that is segregated from the resident fauna and flora in the treatment wetland.

Iron and manganese will remain elevated after the water flows through an anaerobic, deep organic bed, and will be removed subsequently as oxides. Their removal would require an aerating drain or cascade that establishes aerobic conditions. This section of the treatment system also removes residual dissolved sulphide, reoxygenates the water, and leads directly through a vegetated section where flora and fauna flourish. Trace metals that were not previously removed will be adsorbed onto the freshly precipitated iron or manganese oxides. The resulting sequence of treatment units will substantially detoxify the mine water without exposing the biota to contaminants. A vegetated section containing the fauna and flora can follow or be integrated thereafter.

The typical design approach to enhance biodiversity draws on demonstrated rules-of-thumb. Design factors that are positively correlated with increased biodiversity including shoreline complexity, wetland size, vegetative cover of surface area, depth, wetland age, and diversity in macrophyte species (Bennett et al. 2015; Hansson et al. 2005). These design factors reflect accumulated experience, as well as the observation that each species will be drawn towards its own ideal conditions, such as macrophytes colonizing their preferred range of water depths. However, they remain abstract and are not easily understood by decision-makers or stakeholders. Finally, they completely omit from consideration any design aspects that integrate the wetland into the surrounding landscape and broader ecosystem.

This approach was rejected in favour of a wetland designed to support top predators. In this approach, design objectives were formulated as declarative statements, such as “a wetland that supports the doubling of red-backed hawk sightings within the mine site”. This approach is defensible both on theoretical and practical grounds.

Fundamentally, this approach is based on sound ecological principles. In the above example, a wetland that sustains raptors must comprise a food chain of sufficient complexity to support their visits or establishment. Thus, this simple design objective implies a rich and diverse wetland ecosystem, a proposition supported by empirical evidence (Hsu et al. 2011). Despite reports that support this approach, none provide guidance on the design of wetlands that enhance biodiversity and remove contaminants. On a more practical level, having a focused design objective simplifies the design process: we know exactly what we are designing for. Additionally, a declarative design objective makes it easy to convey intentions to decision-makers and stakeholders. Increasing the number of Mountain Caracaras is far more-easily understood than increasing shoreline complexity.

At Los Bronces, the small number of animals identified during annual surveys meant that top predators were easily identified, and their requirements were more readily determined (Biota 2017a, b; Golder 2019). These surveys were used to identify resident and transient species observed at the site and narrowed the selection of species for which to design the wetland. Life histories and habitat requirements for selected species were drawn from various authoritative sources, such as Araya et al. (1993) and Figueroa et al. (2003).

The life histories of top predators found at Los Bronces were used to guide our design for biodiversity. Based on annual surveys, four top predators were identified (Biota 2017b): mountain caracaras (*Phalcoboneus Megalopterus*); red-backed hawks (*Geranoaetus Polyosoma*); barn owls (*Tyto alba*); and Culpeo foxes (*Lycalopex Culpaeus*). Each of these species has broad hunting ranges and diverse diets. This means that a biodiversity design objective such as “establishment of 3–5 breeding pairs of mountain caracaras” is inappropriate due to their broad hunting territories. Instead, the design objectives must be defined in terms of increased sighting frequencies.

The life history of the red-backed hawk is examined to illustrate this process. First, its dietary and hunting habits were examined (Figueroa et al. 2003), then cross-referenced with the ecological report at Los Bronces to confirm the presence of appropriate prey species (Biota 2017b). The latter report confirmed the presence of multiple rodent, small bird, and lizard species. Since their diet is determined by the field abundance of prey species, a wetland that increases their abundance will attract red-backed hawks.

The rodent, small bird, and lizard species all require accessible drinking water, and grain- or berry-producing vegetation to support their populations (Fig. 1). Some of the species of rodents and small songbirds require bushes to construct nests and hide from predators. These needs can partly be provided by a wetland and partly by riparian vegetation. Thus, the wetland design will also support prey bird populations. Additionally, the wetland will be constructed with a soft bottom so that resident amphibians (*Alsodes montanus* and *tumultuosus*) are able to burrow and overwinter.

It was also noted that red-backed hawks hunt from perches, so perch trees were identified as a requirement (Fig. 2). Given that trees will not grow in flooded wetlands, at least at Los Bronces, this leads to the design requirement of an adjacent riparian area that would be flooded periodically during the annual snowmelt. This floodplain will also maintain vegetation that feeds and shelters several prey species. Thus, a wetland that attracts red-backed hawks must be able to overflow during periods of high flows and comprise quieting areas where silt loads can be deposited, allowing the development of a floodplain. Such a design is achieved by constructing very shallow berms, rather than the steep berms most typically used to constrain flows.

This process of gathering ecological information can be repeated for other relevant species, then used to identify areas of overlap. The latter will be incorporated into the wetland design, along with the established ‘rules of thumb’ to enhance biodiversity. The combination of specific design features (adjacent floodplains, shallow accessible pools for access to drinking water, Fig. 3) and broad design (complex shorelines, large surface area, shallow depth, macrophyte cover) make for a flexible and adaptive design process.

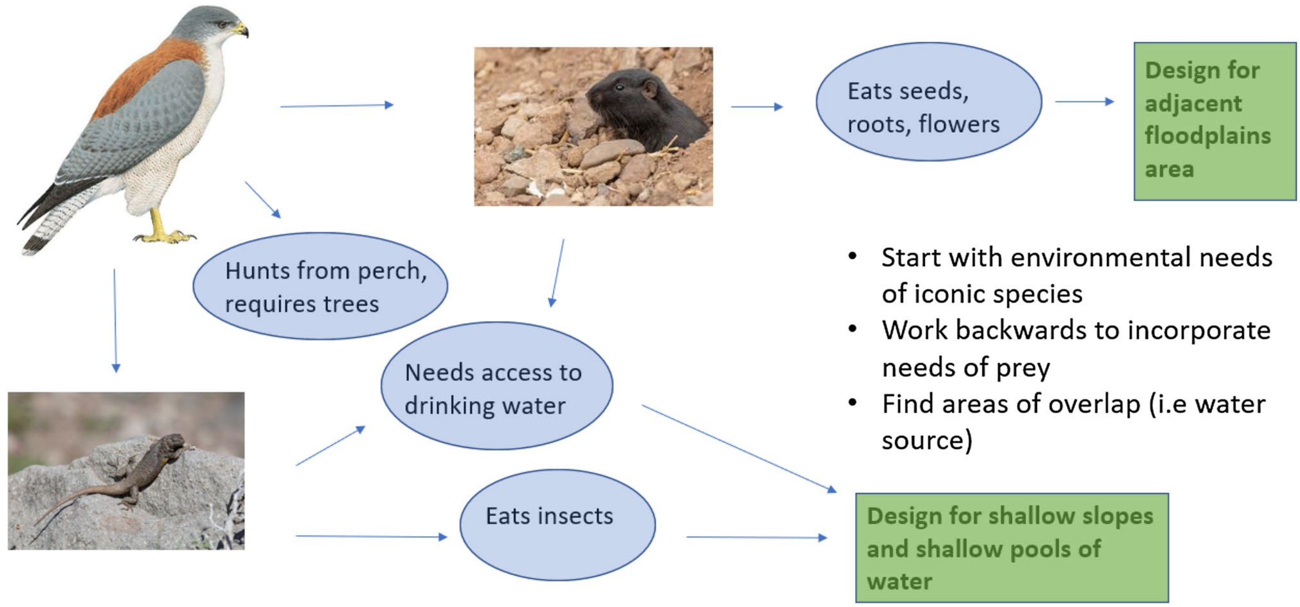

Fig. 1 Life habitat of the red-backed hawk with design implications

Fig. 2 Perch trees allow raptors to hunt nearby wetlands

Fig. 3 Steep banks would prevent access to drinking water for many species

Crucially, the need for floodplains or perch trees flows from an ecological assessment of top predator needs, but not from any established 'rule of thumb' approaches that currently prevails. Nor can it be logically inferred at any point during the process of designing a wetland for water treatment.

At Los Bronces, the annual snowmelt dominates the hydrograph (CONIC-BF 2019). Peak flows reach up to 1000 L/s at that time, whereas low flows decrease to as low as 6 L/s and base flows are maintained around 50 L/s (Fig. 4).

Peak flows are intense, but of relatively short duration. Several measures are available to control and manage these flows:

- Direct flows of contact water to an equalization pond or reservoir and discharge it steadily to the treatment wetland.

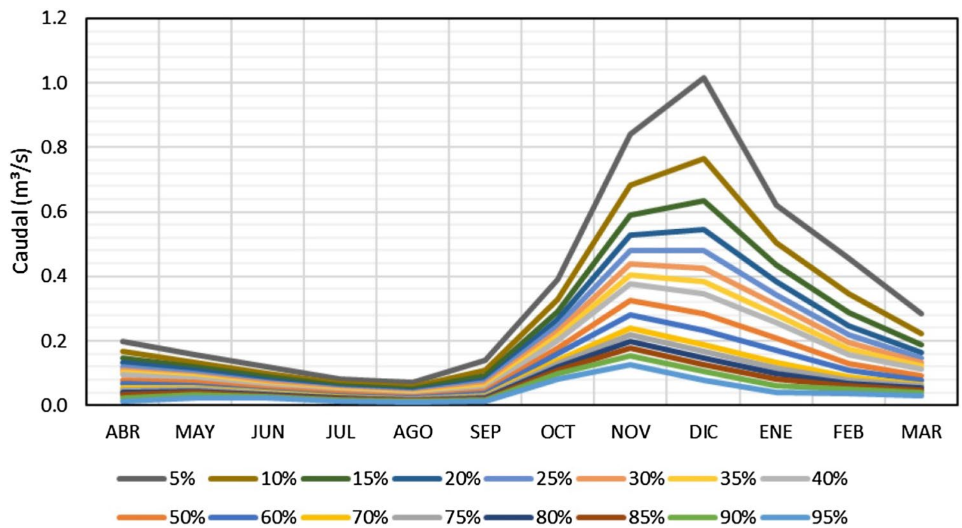

Fig. 4 Hydrograph for flows at the Los Bronces Mine. From (CONIC-BF 2019)

- Create check dams that provide distributed storage to equalize peak flows of contact water.
- Capture clean runoff in diversion ditches and convey it separately to the wetland.
- Create a wetland that can expand and shrink.
- Create broad stilling areas for silt deposition and development of floodplains.
- Create water storage pools and/or floodplain for storage and release.

These measures will all be constrained by the site geomorphology, substrate, surface–groundwater interactions, and flow-related contaminant loadings (either increasing due to flushing effects or decreasing due to dilution). Within these constraints, there is flexibility to modify water flows to suit the design purposes of the ecological treatment wetland.

At Los Bronces, contact water can be collected and conveyed to the mined-out open pit, which will act as a reservoir that equalizes flows of contaminated water. This simplifies the treatment aspects of the system design because an open limestone channel and deep organic bed can be sized for a narrower range of flows and contaminant loadings. However, a broader range of flows favours biodiversity because this will create a range of water depths and gradients of vegetation.

These conflicting requirements are resolved by controlling the flows of contaminated water, but not those of clean runoff. These flows will be separated with diversion ditches that are integrated with the wetland: contact water will flow through the subsurface organic bed and daylight in the aeration cascade where iron, manganese, and residual dissolved sulphide will be removed. Clean water will join effluent from the deep bed and together, these flows, now detoxified, will enter a surface flow wetland. This wetland will be designed using conventional measures to enhance biodiversity. However, it will have very shallow margins, where high flows from snowmelt will overflow into stilling areas, enabling the development of floodplains. The length of the shallow margins and depth of this floodplain will be guided by the site hydrograph. The floodplain area will be designed with stagnant pools that can store and gradually release high flows. Although this is an entirely novel approach for designing a wetland, knowledge and experience obtained with river restoration may be applicable to guide it (e.g. Yochum 2018).

Such a wetland design requires one or more iterations. First, a conceptual design is elaborated that brings together separate elements for water treatment, biodiversity, and water storage/release, as described above. These elements are developed separately and then combined, but a second round of refinements is required to integrate them. In this and subsequent iterations, individual units are resized relative to adjusted water flows and design objectives, and then incorporated within the landscape. Additionally, there must be checks on the distribution of contaminated water and its contact with biota. Temporary exceedances may be tolerable during snowmelt, such as a transient elevation of sulphate levels on the floodplain, but the development of acutely or chronically toxic conditions must be prevented.

This iterative approach is very different from the conventional design approach for treatment wetlands, which are designed following a sequential evaluation of influent characteristics, treatment processes, and sizing of treatment units, followed by increasingly detailed engineering designs. Additionally, the conventional design process neglects ecological considerations, save for the perfunctory consideration of plant selection based on climate and operating water depths. Considerations of fauna typically focus on keeping out nuisance animals that will increase maintenance requirements. The resulting treatment wetlands are isolated from

Fig. 5 Typical treatment wetlands are isolated from their surroundings

the surrounding landscape (Fig. 5) and are designed to function as closed systems. In contrast, ecological development and integration into the local landscape are central to our proposed design approach.

Our ecological approach also differs from most proposed schemes to enhance biodiversity in being guided by ecological interactions, rather than the physical features of the wetlands. Existing approaches to promote biodiversity, such as varying water depth and creating complex shorelines, create opportunities for colonization by different species. It is a kind of beneficial chaos and thus avoids the development of monocultures. However, the requirements for perch trees and floodplains could not have been deduced from these considerations, whereas they followed logically from examining the life habits of the raptors desired at the Los Bronces wetland. Similarly, the requirement for a soft wetland bottom was deduced directly from the life habits of resident amphibians, rather than otherwise.

Another significant difference in the proposed design approach is its relaxation of the requirement to keep all the flows within excavated cell beds. In fact, peak flows are expected to spill over the limits of baseline flows and extend into floodplains. This is a radical departure from conventional designs and raises legitimate concerns about exposure to contaminated water. This concern was identified for the treatment wetland for selenium removal at Chevron's Richmond refinery (Alberta Environment 2005). It was resolved by modifying the first portion of the wetland to sub-surface flow and leaving the remainder as a free surface flow wetland, which supported a thriving bird population. In the Los Bronces design, contact water will flow through a deep, subsurface flow organic bed for nearly complete treatment before it merges with non-contact water and feeds the rest of the wetland.

The above point raises another potential conflict that remains unresolved. While governments are currently promoting the benefits of nature-based solutions and ecosystem services, regulators resist adopting designs of such systems because they contravene existing prohibition for discharging contaminated waters in wetland ecosystems. In one unfortunate case, lightly-contaminated water produced at the Gibraltar Mine was naturally purified in an existing natural wetland, but regulators ordered for this seepage to be collected and pumped back into the tailings impoundment where it originated[1]. The change resulted in a decrease of water flow in nearby Arbuthnut Creek, causing it to dry out during the summer low flow periods. This was far more damaging than any putative impact of metals retained within the natural wetland (which also dried out because its main source of water was removed). In this example, the problem does not lie with the natural wetland that removed metals but with existing regulatory attitudes and practices.

Our proposed approach merges the disciplines of wastewater engineering and ecological restoration and aims to develop ecological treatment wetlands. It draws as much from the sciences of ecology and hydrology as it does from practices of civil or water resource engineering. It merges the strictness of design specifications with the landscape variability that favours biodiversity. In this regard, it is truly an ecological engineering approach to design.

This is not a call for the complete revision of treatment wetland design: current practice is adequate in most cases. However, the design of larger treatment wetlands, say > 5–10 ha, should reconsider some of its assumptions, start to account for ecological considerations, and strive to integrate them in the surrounding landscape.

While the ecosystem services offered by the proposed wetland design are important to Los Bronces and its operator, Anglo American, this design is also very important to the mining industry. New mines are being designed to minimizes the release of contaminants (O'Kane et al. 2019), but there might still be requirements for long-term treatment of dilute contaminated drainage. Treatment wetlands can be incorporated in mine closure plans to remove these residual contaminants, but it is important that these wetlands be self-sustaining to provide long-term treatment. Our proposed design approach aims to establish healthy wetlands that treat water, are integrated within the regional landscape, and insures their long-term sustainability.

The Los Bronces Mine allowed us to examine how different elements of wetland design need to be integrated. However, this was not a complete design, nor is our intention to present a complete set of design guidelines for this new

1 Ben Pierce, Environmental Coordinator, Gibraltar Mine. Personal communication.

approach. Instead, we want to confront the shortcomings of present practices and highlight the need for this new direction. We believe that these new designs will be more complex, but also more viable as long-term ecosystems. We do not claim that this is the only, or even necessarily the best design approach to these systems. Our main intention was to expose the limitations of current approaches and to open possibilities for new ones. We hope that future designers take it as a departure point, rather than a final destination.

Future work should be focused on the development of design principles, guidelines, and practices for these ecological treatment wetlands. Demonstration systems will be needed to convince mining companies and other stakeholders, including skeptical regulators, that this approach is viable and offers benefits unavailable through conventional designs. These systems will need to be incorporated into the design of new landforms at the end of mine life, minimize contaminant release, and protect downstream environments. We look forward to tackling these new challenges.

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