Proceedings Tailings and Mine Waste 2015

Vancouver, BC, October 26 to 28, 2015

Reassessment of best available tailings management practices

Sergio Barrera, Carlos Cacciuttolo
Delfing, Chile

Jack Caldwell
Robertson GeoConsultants, Canada

ABSTRACT

The way in which tailings are managed reflects the history, the regulatory framework and the environment of the country and locale of the mine. In spite of many attempts to find an environmentally friendly strategy for tailings management that considers a balanced relationship between society, ecosystem, and industry, there is no world-wide agreement on what constitutes best available tailings management practices.

Current and developing best available tailings management practices in Chile offer many lessons to mines in other parts of the world. This paper examines the evolution of tailings management in Chile, current practices, and recent proposals for best management practices. It examines the development of Chilean tailings management practices as a response to local environmental conditions, local tolerance for risk, and the influence of practice elsewhere in the world. It includes a review of case histories of Chilean tailings facilities using upstream, centerline, and downstream construction methods; the use of cyclone sand/slime separation; filtered tailings; water use reduction; and ways to avoid failure in a seismic region. Also reviewed are recent proposals for best management practices including dewatering of tailings; the use of Independent Tailings Review Boards; and a risk-based approach to tailings facility design and operation.

The paper concludes that the unique demands on the Chilean mining industry have led to more responsible tailings management practices that have much to offer practitioners in the rest of the world and may lead to the elusive goal of a zero-failure practice.

Keywords: Tailings, management, environment, water recovery, tailings dewatering, dams.

1 INTRODUCTION

Chile has a long, proud history of mining. Today it has one of the world’s most productive and vibrant mining industries. As its mines have grown larger and larger, so too have the Chilean mine tailings facilities. The topography and climate of Chile varies from flat to high and rugged, from arid to wet. Earthquakes are an ever present reality. Water is scarce and farmers guard what little they have. Yet in spite of, or maybe because of, these challenges, Chilean tailings practice is an outstanding in many areas of tailings management. Chilean tailings hold many lessons for other countries facing the challenge of modern mining, extreme climates, and demands for safe tailings facilities.

Chile has had its tailings failures. But after each failure, the lawmakers, the regulators, the consultants, and the industry have moved rapidly and proactively to change and to discard old, inappropriate construction and operating methods. Chile has learnt from tailings practice elsewhere, applied foreign methods, and invariably improved on them. Indeed it may be said that Chile is now a world leader in applying the concepts of filtered tailings, sand-slime separation, thickening of tailings, and the construction of high, earthquake resilient tailings facilities.

This paper is intended to provide history, background, and detail on Chilean tailings management practices to the rest of the world’s tailings profession. It is hoped that the information in this paper may help others in other jurisdictions to take the bold steps that Chile has taken in advancing tailings management and by mutual exchange of experience, opinion, and practice, mining everywhere may be made better.

2 HISTORY OF TAILINGS MANAGEMENT IN CHILE

2.1 The beginnings of mining on an industrial scale in the early twentieth century

Chile had an important mining boom in the middle of the 19th century with the mining of high grade minerals (copper and silver). This mining was done mostly by local entrepreneurs (Pinto 1994). However, all of the high grade mines had finished operations by the end of the 19th century. The exploitation of minerals of lower grade required new technology and larger investment capital (Pinto 1994), neither of which, at the beginning of the 20th century, were available in Chile. It is then that the large foreign companies entered the copper industry as is the case of El Teniente with William Braden in 1905. Later the following foreign companies began operations: Chile Exploration Company Chuquicamata in 1912 and Andes Copper Mining Potrerillos in 1916) (Memoria Chilena, 2015). The dawn of the 20th century (1901) coincides with the invention of the flotation process which allows the separation of the copper sulfide minerals from the components that form the original rock. The emergence of this process was key to developments of low grade mines

The history of tailings management with a large production of tailings starts in Chile at the El Teniente Mine, where the industrial mining of copper was started in 1905, by the American company Braden Copper Company. At El Teniente, between 30,000 and 36,000 tonnes per day (tpd) of tailings were produced in 1915 (Codelco, 2011).

With the objective of avoiding damage to agriculture which could be caused by discharging tailings to rivers, the El Teniente mine company constructed the Arenas and Marga solid material retention impoundments with the tailings in the riverbed of the Coya River (Figure 1). These facilities were later swept away by successive flood events in August 1913, November 1914, January 1915, and June 1960 (Sudzuki, 1964). The tailings flowed in the Coya River and reached the Cachapoal River, which caused the tailings to flow into irrigation channels (Sudzuki, 1964).

The Chilean TSF collapse that has resulted in the greatest loss of human life was the Barahona Tailings Dam in 1928 (Figure 1). The tailings dam is located at El Teniente Mine, about 180 km away from the epicenter at Talca city. The failure of this tailings dam on December 1st, 1928 was the first recorded case of liquefaction-induced failure of a tailings dam in Chile. Failure was caused by an 8.2 Richter-scale earthquake in the central zone of Chile. The tailings dam collapsed as a consequence of this earthquake, breached, and the resulting flow of liquefied tailings destroyed settlements and facilities located downstream and killed 54 people. The seismic event, known as Talca Earthquake, also caused severe damage and casualties in the neighbor provinces of Talca, Curico, Colchagua, and Cachapoal River (Barrera et al., 2015). This caused an enormous impact and damage to agriculture, even disabling parts of some agricultural crop fields.

In February 1939, the naturally occurring Cauquenes pond started to be used as a retention tailings impoundment. Tailings were transported to the pond in a wooden flume, which flowed for 42 km from the concentrator plant at the mountains until it discharged into the pond. At Cauquenes Pond, the suspended slurry tailings were classified by cyclones; these mechanical devices worked by gravity separating the coarse and fine particles. Once the water was decanted on impoundment, occasionally the pond was emptied discharging water (no water reclaim practices was applied), whose waters flowed with the Cachapoal River (Sudzuki, 1964).

In Chile most copper mines are located in the central and northern Andes Mountains. Ore extraction, milling, processing and tailings dumping operations normally take place around the mine pits. For example Potrerillos copper mine disposed mine tailings near the process plant in the beginning of operation (1920-1938). However, subsequently, copper tailings disposal occurred in coastal areas by implementation of off-shore tailings disposal (riverine and marine tailings disposal). This was the case at Potrerillos (1938-1958) and El Salvador (1958-1990) copper mines, located in the Third Region of Chile. El Salvador mine operates at 2,400 – 2,600 m above sea level (a.s.l.) and is located 120 km east of the coastal city of Chañaral. For 52 years (1938-1990) the untreated copper mine tailings (solids, water and chemicals) were routed to the Salado River bed (Riverine Tailings Disposal) and disposed directly onto the sandy beach of Chañaral Bay and Caleta Palitos located at ocean pacific coast (Off-shore Tailings Disposal). This site received 300 and 125 million tons of copper tailings respectively (Figure 1). In March 1990, as a consequence of an Appeal for Protection, the Chilean Supreme Court ruled against the El Salvador Mine and off-shore tailings disposal was banned in Chile (Vergara, 2011).

2.2 Successes and failures in the management of tailings in the mid-twentieth century

In the early 20th century, the main advances in Chilean tailings management consisted of tailings transportation over long distances (about 50 km), where the use of pipes and reinforced concrete canals had been implemented. This served to reduce spills and the use of rivers for tailings transport. However, tailings dam construction – which consisted of upstream dam construction designed and performed by mine operators based on experience using the coarse fraction of the tailings (tailings sand) – was maintained with little variation until 1965 when the tragedy of El Cobre shocked the mining industry and the nation (Barrera et al., 2015). This tragedy set a milestone where it was clear that the technology of the times could no longer be used and it was necessary to introduce big changes to improve the safety of tailings impoundments and enable the mining industry to continue.

It is worth noting that at the time, soils mechanics was still in a nascent phase and there were very few specialists in Chile. Only after this event was it clear to the mining industry that the construction of impoundments required expertise that exceeded the knowledge of the miners. At the end of the 60s, the participation of geotechnical experts in the design of tailings impoundment began. Since most geotechnical knowledge at that time was obtained from water dams, the first reaction was to design dams that utilized borrow materials and were consistent with water dam practice to contain the tailings. We must remember that the tragedy at El Cobre (Barrera et al., 2015) as well as the one at Fort Peck (Davies et al, 2002) discouraged the use of sand in the construction of dams. Therefore, it is not surprising that during the 70s several embankment dams of the type used in water reservoirs were constructed. Examples include Colihues (83 m high earth embankment dam), El Indio (74 m high earth embankment dam), and Los Leones (160 m high rockfill dam) (Barrera et al, 2011). However, the, the use of dams constructed with tailings sands continued in this period with some modifications to their design. Examples of tailings sand dams constructed during this period include the El Cobre Tailings Impoundment No.4 (El Soldado Mine), the Cauquenes Tailings Impoundment (El Teniente Mine), and the Pérez Caldera No. 1 Tailings Impoundment (Los Bronces Mine).

Analysis of what occurred at El Cobre established the need to modify the construction method used for sand dams. This was stated in Supreme Decree No. 86 (1970), where, for the first time in Chile, definitions, criteria, and requirements that must be complied with for the construction and operation of impoundments were established (Figure 1). With this regulation the use of upstream construction was banned – which is a significant step in tailings management practice and is unique to Chile. It is worth noting that this decree only dealt with those impoundments whose dams were constructed with tailings sand, excluding dams constructed with borrow materials (earth embankment or rockfill dams). Implicitly it was recognized that the impoundments with sand dams presented the greatest risk and possibly were the most common types of dams at that time (Barrera et al, 2010). This decree incorporated key geotechnical concepts with regards to material strength and the effect of water on the materials. In addition, it started a new generation of impoundments with sand dams where the sand - in order to be used for construction material - needed to have limitations on the permeability, required a minimum placement density, and mainly the dam needed a robust base drainage system. Examples of impoundments constructed during this period to comply with these requirements include: Pérez Caldera No. 2 Tailings Impoundment (El Teniente Mine), Piuquenes Tailings Impoundment (Andina Mine), and the expansion of the El Cobre No. 4 Tailings Impoundment (El Soldado Mine).

In this evolutionary process, there is an intermediate case: the dam of the Talabre Impoundment. This design was done at the end of the 70s and its construction started in 1983. This dam is constructed with tailings sand but has the following particularities: (i) intermediate inclined drain inside the dam; (ii) downstream slope of 2.5:1 (H:V); and (iii) paddock downstream construction method with mechanical sand transport and placement (instead of the most common hydraulic method) (Barrera et al, 2011).

2.3 Evolution and development in the late twentieth century

The decade of the 80s was a period where there were advances made in the study of the conditions of tailings sand as a construction material for dams. The iconic design of this period is the dam of the Las Tortolas Tailings Impoundment, a key work for the continuity of the Los Bronces Mine which presented the following challenges: (i) mineral transport in a 58 km pipe; (ii) process plant in the valley (far from the mine); and (iii) sand dam of 150 m in height located 40 km from Santiago city. A cyclone sand dam of this height in the vicinity of Santiago city lead to a large effort in studies of sand characterization, design, disposal schemes, and stability-risks analysis. This design was the first to apply the finite difference method in a dynamic stability analysis. The code used in this occasion (1984) was the DSAGE, which later became the FLAC Code. It is also worth noting the design of El Torito (Soldado Mine), which would replace the El Cobre No. 4 Tailings Impoundment, in which the dam was made of tailings sand.

This period marked the wide-spread adoption of cycloned sand dam designs. Cycloned sand dams were later observed to have satisfactorily resisted the March 1985 earthquake (M_w=8.0), with which they showed that a design that controlled the saturation of the sand in the dam were stable during high intensity seismic events.

At the end of the 80s, a new tendency in design appeared which involved the integral management of tailings and waste rock from the mine. Until that date, the use of mining wastes as construction materials and designing waste rock dumps to accommodate tailings impoundments was not even considered, much less applied. During this period, the Romeral Tailings Impoundment (Romeral Iron Mine) which had a tailings impoundment at the side of an existing waste rock dump and construction of the dam with rejected material from the plant (Scognamillo et al, 1999) was constructed. Another project that started in 1989 is the Candelaria Tailings Impoundment (Candelaria Mine) where the location of the impoundment and the material for the dam are part of the design of the waste rock dump. This required a thorough coordination and alignment to balance the management of mining wastes from different sources: mine and plant. These precedents served - during the second half of the 90s - as the basis for the design of the Pampa Pabellon Tailings Impoundment of the Collahuasi Mine (Figure 1).

In the middle of the 90s, and after the successful behavior of the sand dams during the earthquake of March 1985, the design of cycloned sand dams faced the challenge of greater heights. The first case is Quillayes of the Los Pelambres Mine, located in the Andes Mountains, with a 175 m final height. This design incorporated all the innovations introduced to that date and incorporated the first studies of the effect of high stress in the behavior of sands and, also, a 3D dynamic analysis was performed for the first time (Lara et al, 1999; Valenzuela & Barrera, 2003). A few years later, this dam was raised to 198 m to extend the useful life of the impoundment given the increase in mineral production. As a consequence of the limited capacity of the Quillayes Impoundment, the Mauro Impoundment was designed for continuing the operation of the mine (Figure 1). This impoundment – in operation since 2008 – is located 60 km from the plant, with a cycloned sand dam with a final maximum height of 248 m, which for the first time went beyond the 200 m barrier in a high seismicity region (Alarcón & Barrera, 2003). Currently, there are designs for Chilean TSFs that are close to 300 m in ultimate height and, from a stability point of view, there are technical tools to evaluate the stability of these large dams. Great progress in knowledge have been made for the use of cycloned tailings sand under high pressures.

At the end of the 90s, the use of highly thickened and paste tailings began. The thickening of tailings had already been applied in some operations starting in the 80s. Nevertheless, the level of thickening was less than 50%, with which the hydraulic behavior of the tailings slurry was still Newtonian. The Paste Conference developed in Chile (2002) gave a tremendous impetus to this new technology and it started to be included as a disposal option. At the start, this technology was timidly accepted by low production operations (Las Cenizas, Delta Plant) and later was widely applied as it occurred in the rest of the world. Nonetheless, there was reticence to apply it in large mining operations. Minera Esperanza (currently Minera Centinela), which started operations in 2011, took a large step by adopting it for tailings management with a target concentration of 69% and a 90,000 tpd production rate (Figure 1). Recently, the Sierra Gorda Mine (located a short distance away from the Esperanza Mine) is applying it but with a lower concentration of 63% and a 110,000 tpd production rate. One of the main problems of these high thickening operations is the estimate of the tailings beach slope, which has generally been overestimated. This has had a significant impact on the accuracy of the estimated cost of the dams to retain thickened tailings.

3 WORLDWIDE TAILINGS PRACTICE AS IT HAS INFLUENCED CHILEAN PRACTICE

3.1 Implementation of industrial-scale metallurgical processes

The development of large mining at the start of the 20th century in Chile is associated with the appearance of floatation and the arrival of large foreign companies to the copper industry as is the case of El Teniente, Chuquicamata, and Potrerillos. The arrival of foreign companies also brought the available technology of the time, which in general had been developed in countries and zones with no or very low seismicity. Note that in general, early mining operations had relatively low production rates (< 2,000 tpd) and the relatively small amount of produced tailings were often stored in piles or low height deposits and, in some cases, be directly discharged to courses of water. This last was not generally common in Chile given that the mining industry was in the central and northern zone, where the climate is rather desert-like and the courses of water are minor and strongly guarded by farmers.

In these early operations, it was evident that tailings disposal showed a notorious segregation where the coarse fraction was deposited closer to the discharge location and the finer fraction was deposited farther away. In addition to this behavior, the relatively low production rates allowed time for the tailings next to the discharge location to reduce their moisture content and reach a bearing capacity that allowed for transit over the tailings. This characteristic was the birth of the upstream growth method.

The separation between the fine fraction (also called slimes) and the coarse fraction (also called sand) of the tailings was a significant step in tailings management since it resulted in two materials with very different geotechnical properties which could be used in tailings management. The coarse fraction has the consistency of fine sand with a medium permeability, low moisture retention, and a relatively high shear strength. On the other hand, the fine fraction is mainly a sandy silt with low permeability, high moisture retention, and medium strength due to friction and cohesion that is strongly influenced by the moisture content. It was quickly evident that the coarse fraction could be used as a granular material for construction of dams or containment structures for complete tailings or the fine fraction at a very low cost (as compared with other solutions with a borrow dam). Experience showed that these sand dams could be constructed over the slimes and thus started the growth method known as upstream method. This method was quickly adopted and massively diffused. This method was successful mainly because, during the first few years, it was applied in regions with low seismicity (South Africa, Canada, USA, among others). Additional characteristics of early mining operations which were favorable to the use of the upstream method include: (i) coarser milling and (ii) low production rates, which made the construction slower giving more time to the decrease of moisture content in the tailings.

Height	St	Tailings Impoundment	End	Earthquakes	Comment	Mw
49	20	Barahona N°1	1928			
	25					
				1928 quake	Barahona N°1 TSF failure	8.2
70		Barahona N°2				
35	30	El Cobre N°1	1965			
	35					
52		Cauquenes	1977			
		Chañaral disposal	1990			
				1939 quake		7.8
	40					
	45					
	50					
	55					
	60			1960 quake	Greatest earthquake recorded	9.5
	65			1965 quake	El Cobre village covered with tailings	7.4
55		El Cobre N°4				
55	70	Piuquenes	1979			
				1971 quake		7.5
83	75	Colihues	1986			
35		Romeral				
110	80	Pérez Caldera N°2	1991			
160		Los Leones				
48	85	Talabre with dam		1985 quake		8.0
140		Carén				
27		Pampa Austral				
	90					
150/100		Las Tórtolas / El Chinche				
		El Torito				
172 / 72		Candelaria / Tambo 1	/1998			
	95					
59		Pastos Largos	2002			
180 / 60		Pampa Pabellón / Tambo 2	/2000			
198		Quillayes	2008			
120	'00	Ovejería				
80/50		Laguna Seca / las Cruces				
50	'05	El Trigo				
237		Mauro				
140	'10	Andacollo		2010 quake		8.8
40		Esperanza				
66/260		Sierra Gorda / La Brea				
	'15					

Figure 1. Time Line of Tailings Impoundments in Chile.

In general, the flotation process technology that arrived in Chile at the start of the 20th century produced tailings with a solids concentration between 27 and 33% by weight. As there were generally no restrictions on water use, the tailings were not thickened and were discharged with this water content in the impoundment. At first, the environmental differences in Chile were not considered, particularly the seismic aspect which would later have tragic consequences. Early examples of this technology are the impoundment of Barahona and Cauquenes of the El Teniente Mine and the El Cobre 1 of the El Soldado Mine. This technology was applied without major modifications until 1965 when the El Cobre tragedy - as mentioned above - made it necessary to introduce major changes in tailings management to assure the stability of the structures. The period from 1965 to 2000 was mainly dedicated to develop a local technology with little influence from external models. In the case of cycloned sand dams, the barrier of 150 m in height was surpassed in a seismic zone and served as a basis for the construction to greater heights (as it happened at the beginning of 2000). Also in this period, the design of waste rock dams was advanced, introducing the construction of large dams with thick layers and compaction only provided by the transit of large mining trucks.

3.2 Risk considerations on tailings management

Environmental conditions particular to Chile include: climatic (extremely dry and wet in different zones); high seismicity (extreme events of great magnitude and dynamically active geomorphology); and variable topography (flat desert terrain and mountain ranges with steep topography). These conditions result in a latent exposure to disasters due to natural hazards (earthquakes, tsunamis, floods, volcanic eruptions, etc.). This background is important to the issue of safe tailings management and risk mitigation.

Management of tailings in Chile during the twentieth century has been carried out under a reductionist approach to risk. There has been progress towards a holistic risk approach rather than taking what may be called an incipient approach. That is why it is necessary to clarify the difference between environmental risk and potential risk threat as probability of occurrence of an unwanted phenomenon (the terms "hazard" and "risk"). This clarification represents an overcoming of overly reductionist ideas of risk in which the phenomenon in question is treated as if it were an objective property evaluated in probabilistic terms (Sauri, 1995). The tailings management experience in Chile under foreign influence risk management simply based on probabilistic calculations did not take into account the multiplicity of factors involved in its gestation (environment preservation, society vulnerability, extreme earthquakes, floods, among others).

Under a new approach, risk management under a holistic vision in both design and operation of tailings deposits, it is necessary to overcome the dichotomy "natural risk / technological risk" and a new concept such as "environmental risk" is proposed. Environmental risks are defined as those (natural) geophysical extreme events and technological accidents characterized by the concentrated release of energy and matter that pose an indirect threat to human life and that can result in impact significant to people and the environment (Sauri, 1995).

Finally the holistic approach to risk management in tailings acknowledges and agrees that technological risks are caused by major failures or malfunctions of human systems, but also often as system failures related to regulatory, economic rationality and social factors. Technology is not an autonomous force but is a form of social knowledge that depends on the distribution of responsibility and environmental planning between different social groups.

3.3 Environmental considerations on tailings management

In Chile, environmental awareness first arose in the 50s and did not reach satisfactory results until 1990; it was a slow process with much debate and conflict. The environmental focus in the mining of the 90s involved the confluence of four forces: (i) the return of transnational mining companies (these companies that had come to Chile in the 80s incorporated environmental management as a key variable in the business, promoting a more sustainable industry); (ii) the internationalization of the economy (negotiated free trade agreements included commitments to approve environmental quality standards and promote the use of clean technologies to protect the environment); (iii) public awareness about environmental issues (public participation in lawsuits as was the Chañaral tailings case, considering the participation of academic and scientific community in promoting public policies); and (iv) the country's democratization, where during the eighties the Chilean environmental movement was consolidated in the 90s achieving political consensus (Folchi, 2010).

The decade of the 90s was a time of transition for Chile; this is also true in environmental matters. Between 1990 and 1999, the CONAMA (National Environmental Commission) was created, the Draft Law on Environmental Bases (1992) and Regulation System of Environmental Impact Assessment (1997) was prepared and some additional emission standards were developed (Folchi, 2010). This clearly marked a major milestone in the management and handling of tailings from the mining industry in Chile; the result was a constant process of improvement. But debate is still brewing today, conversations continue regarding the viability of continuing with on land tailings disposal or explore submarine tailings disposal.

With the arrival of the new millennium, water supplies became more critical for mining. In fact, all of the northern area in Chile is very arid and sources of water are scarce and mainly located in the Andes Mountains. This limitation of water supply was a great promoter for exploration of new options and technologies to reduce the water losses in tailings management. The thickening and paste technologies came from abroad and gained acceptance and quickly gained the approval from the authorities and community, which saw a beneficial combination to reduce the consumption of water and, in turn, to deposit tailings with lower moisture and therefore greater strength (contrary to conventional tailings). Other technologies that point in the direction of reducing the consumption of water are the splitting of sands and slimes, and filtration of tailings. Currently there is a wide range of technological options to manage tailings -- the selection of the technology to be applied is done with a technical, economic, environmental, and risk analysis, which also incorporates the option of water supply from the sea. This selection always considers an important level of thickening although not restricting it to the level of paste.

4 CURRENT CHILEAN TAILINGS MANAGEMENT PRACTICES

Currently, many major copper mining projects in extremely dry areas, as in northern of Chile, process sulfide ores at high production rates; in some cases over 100,000 tpd. The result is the generation of large amounts of tailings that are commonly managed and transported hydraulically using fresh water to tailings storage facilities (TSF).

Considering the extremely dry climate, water scarcity, community demands, and environmental constraints in these desert areas, the efficient use of water in mining is being strongly enforced. For this reason, water supply is recognized as one of the limiting factors for the development of new mining projects and for the expansion of the existing ones in these areas. New water supply alternatives such as seawater (desalinated or not) or water recovery from tailings, represent the strategy developed by the mining industry to deal with this growing scarcity (Cacciuttolo et al, 2015a).

The transport and storage of tailings require environmental management. This residue is generally managed and transported hydraulically using water -- this alternative is cheaper than bulk transportation by conveyor belts, trains or trucks. For an environmentally friendly and sustainable practice, most of water used for tailings transportation should be recovered for reuse in the metallurgical process (Cacciuttolo et al., 2015a).

Copper production is growing quickly in Chile, and part of the increasing water demand can be explained by the expansion of existing mines and new projects. In addition, there is an important increase in mine production rates due to declining copper grades at existing mines. As copper grades decline, more ore needs to be processed in order to produce the same amount of copper. The use of water is proportional to the amount of ore that is processed, so it follows that more water is needed to produce the same amount of copper when grades decline. The exploitation of large ore deposits with decreasing grades has led to the need to use efficient, large equipment for the milling and processing of ore which enables higher production rates, which in turn implies an increased water demand for metallurgical process (Cacciuttolo et al, 2015a).

The application of tailings dewatering technologies for increasing tailings water recovery is a relevant step to reduce water losses (water from fresh or sea water supplies) caused by evaporation, infiltration and retention at interstitial voids on TSFs. Figure 2 shows new designs and technologies applied in Chile in order to achieve an environmentally friendly tailings management focus on efficiency water use.

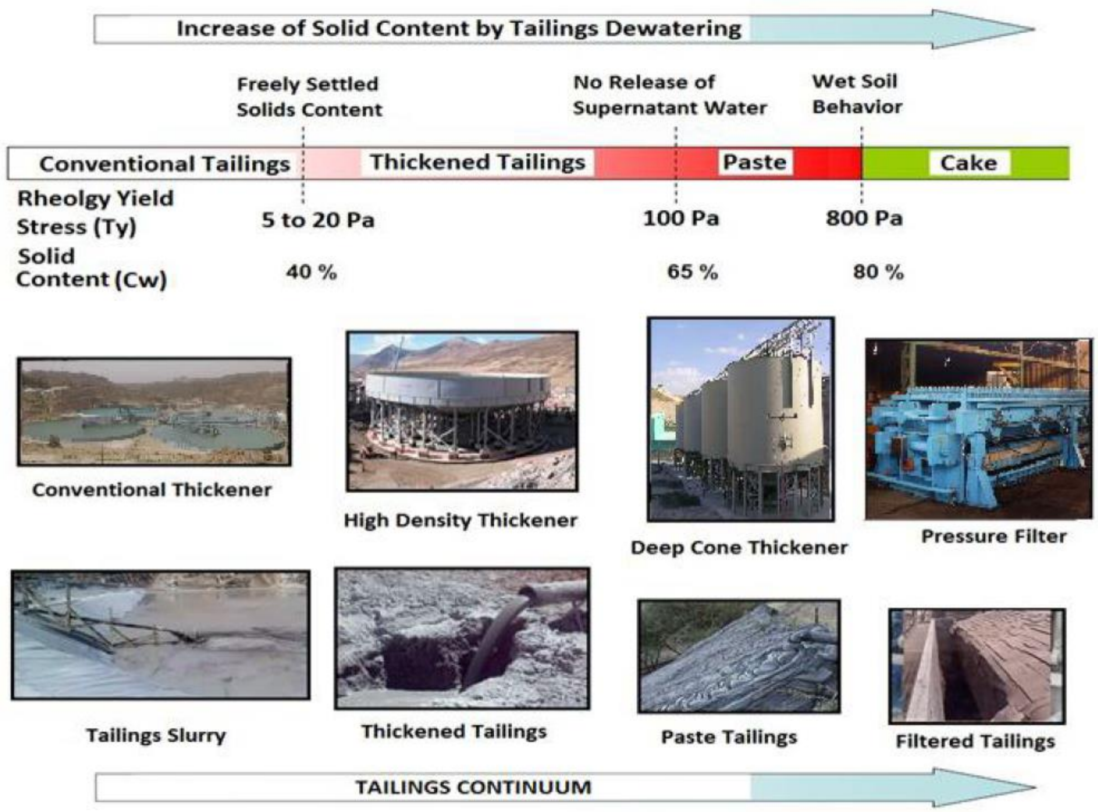

Figure 2. Tailings Dewatering Technologies Applied in Chile (Cacciuttolo et al., 2014b).

4.1 Water Recovery from Tailings with Conventional Technologies (WRCT)

Currently, Chilean large scale mining in dry climate areas, typically utilize tailings disposal schemes that consist of conventional or slightly thickened tailings. Tailings solids weight concentrations between 48 and 52% are typical for these operations. Conventional TSFs have dams built of cycloned tailings sands (coarse fraction of tailings obtained by hydrocyclones), or have a slightly thickened tailings deposit with dams built of borrow material. Conventional tailing dams have very variable water recoveries ranging from 0.36 to 0.70 m^3/ton of tailings in well operated TSFs. Well operated TSFs are considered to have appropriate tailings distribution systems, good control of the pond (volume and location) and adequate seepage recovery. In conventional dams, water decanting at the settling pond is recovered by floating pumps, or decant towers, and dam seepage is collected by a drainage system and cut-off trench systems. However, a high seasonal evaporation rate can substantially reduce water recovery from the pond area, and infiltration from that part of the pond in contact with natural soil can produce water losses. Examples of this technology are Las Tortolas, Candelaria, Laguna Seca, Quillayes, Talabre, and Pampa Pabellon tailings management history cases.

4.2 Water Recovery from Tailings with Thickening Technologies (WRTT)

Thickened Tailings Disposal (TTD) technology requires more field experience than conventional tailings disposal to evaluate its performance. In the conventional approach, the properties of tailings are fixed by the concentrator plant, whereas in a TTD impoundment, the properties of the tailings and their placement are "engineered" to suit the topography of the disposal area. The behavior of tailings in both approaches is entirely different. In conventional disposal, tailings segregate as they flow and settle out to a quite flat deposit (tailings beach slope < 0.5%), whereas in TTD technology a sloping surface is obtained. The main difference is that in TTD technology tailings are thickened to over 60% before discharge with a homogeneous, heavy consistency that results in laminar non-segregating flow from discharge. In this way TTD produces water recovery as high as 0.40 – 0.60 m^3/ton of tailings range and a self-supporting deposit with sloping sides, requiring small dams (Robinsky, 1999). Examples of this technology are Cerro Negro Norte, Esperanza (Centinela), Sierra Gorda, Las Cenizas, and Delta TSFs.

4.3 Water Recovery from Tailings with Filtering Technologies (WRFT)

In the last 20 years, many mining projects around the world have applied a tailings disposal technology called filtered dry stacked tailings. This technique produces an unsaturated cake that allows storing this material without the need to manage large slurry tailings ponds. The application of this technology has accomplished: (i) an increase of water recovery from tailings by reducing water losses to 0.20 – 0.40 m^3/ton of tailings range; (ii) reduction of TSF footprint (impacted areas); (iii) decrease in the risk of physical instability, as the TSF is a self-supporting structures due to compaction (such as dry stacks); and (iv) a better community perception. The improvements of filtering technologies (pressure and vacuum filtering, and dewatering by vibrating screens) in recent years has allowed for improvements in operational reliability and the development of large capacity filters, reaching 50,000 tpd in some projects (Cacciuttolo et al, 2014b). Examples of this technology are La Coipa, El Peñon, El Indio, El Toqui and Mantos Blancos tailings management history cases.

4.4 Water Recovery from Tailings with Hybrid Technologies (WRHT)

The future trend in Chilean mining will be the complementary supply of seawater and fresh water, with the greater supply being from sea water. Along with this, implementation of dewatering tailings technologies depending on the characteristics of the mineral (grain size, hardness, specific gravity, chemical composition of tailings, etc.), promote high water recovery from tailings by reducing water losses to 0.30 – 0.50 m^3/ton of tailings range. An alternative process to obtain filtered tailings consists of the recovery of the coarse fraction of tailings (cycloned tailings sand) through two cycloning stages followed by a drainage stage in dewatering vibratory screens to reduce tailings moisture and turn it into a paste easy to transport to the adjoining dumping facility (Cacciuttolo et al, 2014a).

Figure 2. Hybrid Technology Applied in Chile – Mantos Blancos (Cacciuttolo et al., 2015c)

4.4.1 Sand Slimes Splitting Technology

Tailing slimes are very fine materials that retain much water once deposited. This results in higher water losses because of entrapped water in the interstitial voids of the slimes. Also, the resulting tailings have a very low permeability of the order of K ~ 10^{-6} cm/s (Barrera, 1998). To reduce water losses in slimes, it is possible and may be desirable to thicken the slimes before depositing them – this approach has become a very attractive method. Thickening of the slimes presents some critical issues regarding thickening performance depending on mineralogy of ore, and fines content of slimes (clay). Dewatering of tailings sand is much easier as it is a coarse material (total tailings coarse fraction) known to drain water once deposited. The permeability of tailings sand is on the order of K ~ 10^{-4} to 10^{-3} cm/s (Barrera et al., 2011).

If total tailings are classified with cyclones, and the sand slimes splitting ratio (sand/slimes) obtained is high, such 60/40, the global water recovery of water will be greater than the total tailings disposal without cyclone separation, because a larger amount of tailings sand will have low amount of fines, implying high tailings sand permeability, resulting in the increase of water recovery, supported by a robust drainage and seepage collection system.

As mentioned above, individual technologies (including classification, transport and disposal of tailings, tailings sand and slimes) part of Sand Slime Splitting method, are well understood from operational point of view, associated to large tailings production rates, being proven in recent decades (Barrera et al., 2011). This is a good indicator, maybe a proof, of the technical feasibility and reliable performance of this method in combination mode (Barrera, 2009). Examples of this technology are Caserones and Mantos Blancos TSFs.

The following table shows Chilean experience on tailings management and water efficiency:

Table 1. Tailings management methodologies and average water make-up (TSF water losses)

Tailings Management Methodology	Tailings Storage Facility Name	TSF Disposal and Water Management			Reference
		Production Rate (tpd)	Solids Content C_w (%)	Average Make-up (m^3/ ton)	
WRCT	Pampa Pabellón	120,000	52 (TT)	0.70	Wels et al. (2003)
WRCT	Talabre	160,000	55 (TT)	0.64	Wels et al. (2003)
WRCT	Quillayes	115,000	40 (SL)	0.35	Samad (2013)
WRTT	Esperanza	95,000	65 (TT)	0.50	Samad (2013)
WRTT	Cerro Negro Norte	20,000	65 (TT)	0.45	Pino (2013)
WRCT	Laguna Seca	240,000	50 (TT)	0.66	Chambers et al. (2003)
WRCT	Candelaria	75,000	52 (TT)	0.40	Wels et al. (2003)
WRFT	La Coipa	20,000	80 (TT)	0.22	Lara et al. (2012)
WRFT	Peñón	3,000	84 (TT)	0.25	Lara et al. (2012)
WRHT	Mantos Blancos	12,000	82 (SL & CS)	0.28	Lara et al. (2012)
WRHT	Caserones	90,000	60 (SL & CS)	0.37	Barrera (2009)
WRTT	Las Cenizas	2,500	65 (TT)	0.39	Flores (2011)
WRTT	Delta	2,000	60 (TT)	0.48	Diez (2011)

Note: The following terms mean:

TT: Total Tailings, SL: Slimes (fine fraction of total tailings) and CS: Cycloned Sand (coarse fraction of total tailings).

5 LESSONS LEARNT THAT MAY GUIDE OTHERS

More efficient and economical tailings preparation and disposal techniques are being introduced at Chilean mine sites. Some of these systems achieve greater efficiency and economy by removing excess water from the tailings at the processing plant before transport. This maximizes the recovery of water and process chemicals for re-use and minimizes the discharge of contaminants, thereby reducing the risk of seepage or release to surface waters.

It is important to mention the following tailings management practices that have been developed in Chile:

- Feasibility of building cycloned tailings sand dams using appropriate technology.
- Tailings management integrated with waste rock management (ensuring that co disposal of tailings and waste rock is not generating acid mine drainage).
- Implementation of tailings disposal technologies to reduce water losses.
- Integrated approach to site selection and technology (considering technical, economic, environmental and risk issues).
- Use of seawater for tailings transportation (in dry climates with freshwater shortages).

- Application of highly thickened tailings technology.

The traditional design approach is based on a design life for the facility and long-term physical stability, together with a design "factor of safety". While the design life of a tailings storage facility can be reasonably well defined, its design life after closure is more contentious, with the implications that this is in perpetuity. The use of a design factor of safety implies that providing this is achieved, uncertainties can be ignored. The high level of uncertainty that is often associated with TSFs requires a high factor of safety to ensure an acceptably low probability of failure. This approach can lead to an inefficient design on large time scale (DITR, 2007).

On the other hand, tailings management considering a future view based on the principles of sustainable development and with a compelling business approach, needs to focus on driving the design, operation, closure and rehabilitation of tailings storage facilities towards:

- Filtering, thickened and paste tailings disposal, to reduce water use and seepage, and to produce a more stable tailings deposit in the long-term;
- Implementation of tailings management strategies and technologies that provides physical, chemical and hydrological stability of TSFs for the operation, closure and post closure stages, considering not only technical, economic and risk aspects but also environmental, social and health issues;
- Tailings landforms aligned with natural landscapes and community expectations;
- Reduction of tailings volume production, recycling and reuse (metallurgical tech advances);
- The precautionary approach with more rigorous studies (baseline with adequate time-space scale) and relevant ecosystem impact assessment when considering proposals for Deep Sea Tailings Disposal (DSTP);
- Adequate use of territory, carry out a strategic environmental territory planning which includes: social, economic, and a long term politics;
- Independent Tailings Review Boards those are active during operation, closure and post closure.

The principles of leading practice tailings management are underpinned by a risk-based approach to planning, design, construction, operation, closure and rehabilitation of tailings storage facilities. In taking this approach, plans need to be tailored to manage a tailings storage facility effectively over its full life, with sufficient detail to manage the potential risks within acceptable limits. A risk-based design approach provides a framework for managing the uncertainty and change associated with tailings storage facilities and has a number of benefits (DITR, 2007), including:

- Improved quantification of the magnitude and costs of exposure to hazard;
- Provision of a defensible argument for the adoption of the optimum strategies;
- Identification and elimination of low risk hazards;
- Highlighted significant risks that need to be reduced by appropriate treatment measures.

The attractiveness of reducing the costs of tailings management in the short-term must be carefully weighed against the possibility of increasing environmental and social costs at closure and beyond. This requires a robust and flexible risk-assessment model and associated cost-effectiveness analysis to aid the decision-making process throughout the mine life cycle (DITR, 2007). Public health and safety risks and broad social and environmental impacts need to be considered, including situations where contaminants could be released to the environment over the long-term.

6 OPPORTUNITIES FOR IMPROVEMENT IN CHILE AND WORLDWIDE

There are many challenges that must be overcome in Chile and worldwide to achieve a safe tailings management state-of-the-art outcome. Traditional tailings disposal methods create environmental problems as they can: (i) take up large surface areas; (ii) be highly visible; (iii) entrain and possibly store large volumes of water; (iv) seep unwanted water into the ground; (v) release TSF drainage into surface streams; and (vi) cause dust problems.

Avoiding these issues, and their associated risks, requires a commitment to rigorous planning and application of leading practices over the full mine life cycle. Such outcomes also require foresight and recognition that tailings facilities can incur environmental and social costs in the long-term if leading practice principles are not heeded. TSFs must meet operator, public health and safety, community, and environmental protection objectives. These objectives can only be met if TSFs are designed, operated, closed and rehabilitated to a level of risk that is acceptable to stakeholders for the full operating life of the facility and beyond. A systematic approach to effective tailings management is therefore advocated. Management strategies need to be risk-based and account for the viewpoints and expectations of the communities in which companies operate (DITR, 2007). The main tailings-related risks to people and the environment can be characterized for the operational and closure phases. The principal objective of a TSF is for tailings solids and any stored water to remain contained.

The risk-based approach applied to tailings management must have sufficient flexibility to allow changing circumstances to be managed. These changes could involve routine and anticipated TSF raises, unforeseen expansions, or bringing on-line completely new facilities and/or new disposal methodologies (DITR, 2007).

The definition of value according to the theory of value is: any action or proceeding to be conducted that leads to realize a certain goal. Under this view and having defined a spatial-temporal scale, the evolution of tailings management in Chile during the twentieth century has made progress on technical and economic aspects, with recent significant environmental progress over the past two decades. This undoubtedly is valuable, and efforts are recognized for managing tailings controlled and physically stable. They are still pending issues in the pursuit of an integrated or holistic management of tailings management, which requires an interdisciplinary approach involving professionals who can support the physical, geochemical and hydrological stability of tailings deposits, with measures and techniques for the stages of design, operation and closure. Hard work and dedication has been carried out in technical, economic, risk, environmental and social studies, showing that this has led to better decisions recently, which reduce the negative environmental impact, allowing anticipating potential damage and to mitigate or eliminate adverse effects.

For this reason, it is important to perform further studies for unknown natural sites, such as the bottom of the ocean, and so have enough information to make responsible decisions and long term vision. Impacts and adverse effects on the human population and the environment, still not fully understood and internalized are reflected in the case of Chañaral described above. Thus it seems unreasonable to make a decision to place the tailings in the ocean without knowing for certain the consequences or effects. An important and not lesser aspect is also respect of the agreements signed by Chile regarding the handling of waste in the ocean protocols - Protocol and London Convention (IMO, 1996), which were backed by national authorities at international meetings looking for a friendly management of wastes in the ocean. Chilean experiences described in this article represent a contribution, which must be considered for regulators to use a precautionary approach, more rigorous and relevant socio-environmental assessment when considering they are faced with considering proposals for DSTP in waters of their jurisdiction. Considering this, a decision with socio-environmental approach must be taken by the authority in order to permits with clear restrictions/limitations or banned DSTP technique in Chile.

It is important to develop and implement a closure and post-closure plan that provides physical, chemical and hydrological stability. An interdisciplinary dam safety review of abandoned tailings dams should be urgently carried out and physical-hydrological-geochemical stabilization solutions should be implemented to prevent potential future tailings collapses and deaths from these facilities. This requires Independent Tailings Review Boards, periodic inspection, monitoring plans, and on land planning of the tailings deposits during operation and after closing, in order to control the behavior of the tailings over time, to protect the environment, people's health, and wellness of cultures' livelihood (Cacciuttolo & Tabra, 2015b).

7 CONCLUSION

This paper has surveyed the history of tailings management in Chile. This is a story of over one hundred years as the profession advanced from simple methods through failures, reform, adoption of improved approaches, and ultimately the implementation of the newest and best procedures. The ability of Chile to now construct high tailings facilities that resist earthquakes, require less water use, and are better integrated with the environment is a testament to Chile's professionals, its politicians and regulators, and its public.

Chilean tailings practice has never stood still. It has been fast to adopt better practices from abroad, it has been fast to learn from failures. It has been quick to innovate and use better methods. Its public and regulators have been proactive and positive in banning unsuitable approaches, passing appropriate laws, and implementing reasonable regulations that have both prompted the mining industry to innovate and that have led to protection of the environment.

The story told in this paper attests to the fact that an environmental mining focus can result in responsible mining. A society and new generation of critic professionals that are dynamic and open to change can advance and can continue to the benefit of society and road to a sustainable mining. A philosophy of continuous learning, of adaptation of the best practice wherever it originates, and a boldness to act are the hallmarks of Chilean tailings practice. We submit that the story of tailings management in Chile holds lessons for other places. For there is no doubt that Chilean practicioners have experience to share on tailings management, but there are still pending social and environmental issues, and lack of development of TSFs closure. Chilean tailings management practices will continue to evolve, the world will continue to contribute and continue to be able to learn from what is done there.

8 REFERENCES

Alarcón, J.C. & Barrera, S., 2003. "Dams of Great Height, a Challenge". Symposium of Tailings, ICOLD, Montreal Barrera, S., Valenzuela, L. and Campaña, J. 2011 "Sand Tailings Dams: Design, Construction and Operation". Tailings and Mine Waste 2011, Vancouver, BC. November 2003.

Barrera, S., (1998), " Deposition densities of tailings in Chilean deposits", Proceedings of the 5th International Conference on Tailings and Mine Waste, January 1998, Fort Collins, CO, USA.

Barrera, S., & Riveros, C. (2009),"Caserones: Option of tailings classifying to improve water reclaim", Proceedings of 12th International Conference on Paste & Thickened Tailings, April 2009, Viña del Mar, Chile.

Barrera, S, Cacciuttolo, C, & Urquidi, J, (2015) "A Review of the Performance and Effects on Chilean Large Tailings Storage Facilities", Proceedings of 3rd International Seminar on Tailings Management Tailings 2015, Santiago, Chile.

Cacciuttolo, C. & Scognamillo, C., (2014a), "Improving Water Recovery with Different Tailings Management Technologies", Proceedings of 4rd International Conference on Water Management in Mining WIM 2014 Conference, Viña del Mar, Chile.

Cacciuttolo, C, Barrera, S, Caldwell, J, & Vargas, W, (2014b) "Filtered dry stacked tailings: Developments and new trends", Proceedings of the 2nd International Seminar on Tailings Management Tailings 2014, Antofagasta, Chile.

Cacciuttolo, C., Tabra, K. & Sandoval, M., (2015a), "Efficient Use of Water in Tailings Management: New Methodologies for the Future", Water Week Latinoamerica 2015 Congress, Viña del Mar, Chile.

Cacciuttolo, C. & Tabra, K. (2015b). Water management in the closure of tailings storage facilities. International Conference of Acid Rock Drainage and International Mine Water Association (ICARD – IMWA 2015), Santiago, Chile, April, 2015.

Cacciuttolo, C., Barrera, S., Astete, A. y Bouso, J.L., (2015c),"Dewatering Tailings on Horizontal Vibration Screens: An Alternative to Filtration Systems to Obtain Tailings to be Dispose at Dry Stack Tailings Storage Facilities", Seminar on Tailings Management, Tailings 2015, Santiago, Chile.

Chambers, B., Howard, P. Pottie, J., Murray, L. & Burgess, A. (2003),"Water recovery from a mine in the Atacama Desert", Proceedings of 10th Water in Mining Conference, October, Brisbane, Australia.

Codelco (2011). El Teniente: Una historia de más de un siglo. Revista preparada por Direccion de Comunicaciones Gerencia de Sustentabilidad y Asuntos Externos, División El Teniente, Codelco.

Davies, M.P., E.C. McRoberts and T.E.Martin (2002). Static Liquefaction of Tailings – Fundamentals and Case Histories. In proceedings Tailings Dams 2002. ASDSO/USCOLD, Las Vegas, USA.

Department of Industry, Tourism and Resources (DITR) (2007). Tailings management, Leading Practice Sustainable Development Program (LPSDP) for the Mining Industry. Department of Industry, Tourism and Resources, Canberra, Australia.

Diez, A., (2011). *Experiencia de los relaves en pasta de Delta.* In 3rd Paste Tailings Seminar, RELPAS, Santiago, Chile.

El Cobre. Avaliable at: http://www.educarchile.cl/ech/pro/app/detalle?id=204855 (Accessed: July 2015).

Flores, I., (2011). *Disposición de relaves en pasta en faena Cabildo.* In 3rd Paste Tailings Seminar, RELPAS, Santiago, Chile.

Folchi, M. (2010). La gestación de la política ambiental minera antes de la «Revolución ambiental de los noventa». Libro Medio Ambiente y Sociedad: Conceptos, Metodologías y Experiencias Desde las Ciencias Sociales y Humanas. ISBN: 978-956-284-727-8, Ril Editores, 2010.

IMO (1996). London Convention and Protocol. Available online: http://www.imo.org/.

Lara, J.L., Gómez, P. & Barrera, S., (1999). "Análisis Dinámico Tridimensional Presa de Arena de Relaves Quillayes Pelambres-Chile", XI Conf. Panam. Mec. Suelos e Ing. Geot., Foz do Iguaçu, Brasil.

Lara, J. L., Pornillos, E. & Loayza, C. (2012), " The application of highly dewatered tailings in the design of tailings storage facilities – Experience in mining projects in Peru", Proceedings of the 16th International Conference on Tailings and Mine Waste, October 2012, Keystone, CO, USA.

Memoria Chilena (2015). Available at: http://www.memoriachilena.cl/602/w3-article-3632.html (Accessed: July 2015).

Pino, R. (2013) Depositacion de Relaves Espesados en Proyecto Cerro Negro Norte. *5th Paste Tailings Seminar, RELPAS*, Santiago, Chile.

Pinto, J. 1994."Historia y Minería en Chile: Estudios y Fuentes". América Latina en la Historia Económica. Boletín Instituto de Investigaciones Dr. José María Luis Mora, Número 1, Enero-Junio. 1994.

Robinsky, E.I., (1999). *Thickened Tailings Disposal in the Mining Industry.* E.I. Robinsky Associates Ltd., 1 Lydia Court, Toronto, Canada.

Samad, M. A. & Singh, S. (2013),"Mine water management strategies in dry areas of Chile", Proceedings of 1st International Conference on Mine Water Solutions, April 2013, Lima, Peru.

Sauri, P. (1995). Geografía y riesgos tecnológicos, Documents d´Analisi Geográfica, 27, pp. 147-158.

Scognamillo, C. & Barrera, S., 1999. "Tailings Deposits with waste Dams", Tailings and Mine Waste '99 Conference, Fort Collins, Colorado, USA

Sudzuki, F. (1964). Relaves de cobre y aguas de riego en río Cachapoal. Agricultura Técnica, Chile, 1964.

Valenzuela, L. & Barrera, S., 2003. "Seismic Design of Los Quillayes Tailings Dams in Chile". 12th Panamerican Conference on Soil Mechanics and Geotechnical Engineering, Cambridge, MA

Vergara, A. (2011). "Cuando el río suena, piedras trae": Relaves de cobre en la bahía de Chañaral, 1938-1990. Cuadernos de Historia, Universidad de Chile. 2011, N° 35, p. 135-151. ISBN 0719-1243.

Wels, C. & Robertson, A. (2003), " Conceptual model for estimating water recovery in tailings impoundments", Proceedings of 10th Conference on Tailings and Mine Waste, October 2003, Vail, CO, USA.