Overview of the Use of Flooding to Minimize Metal Leaching and Prevent Acid Rock Drainage

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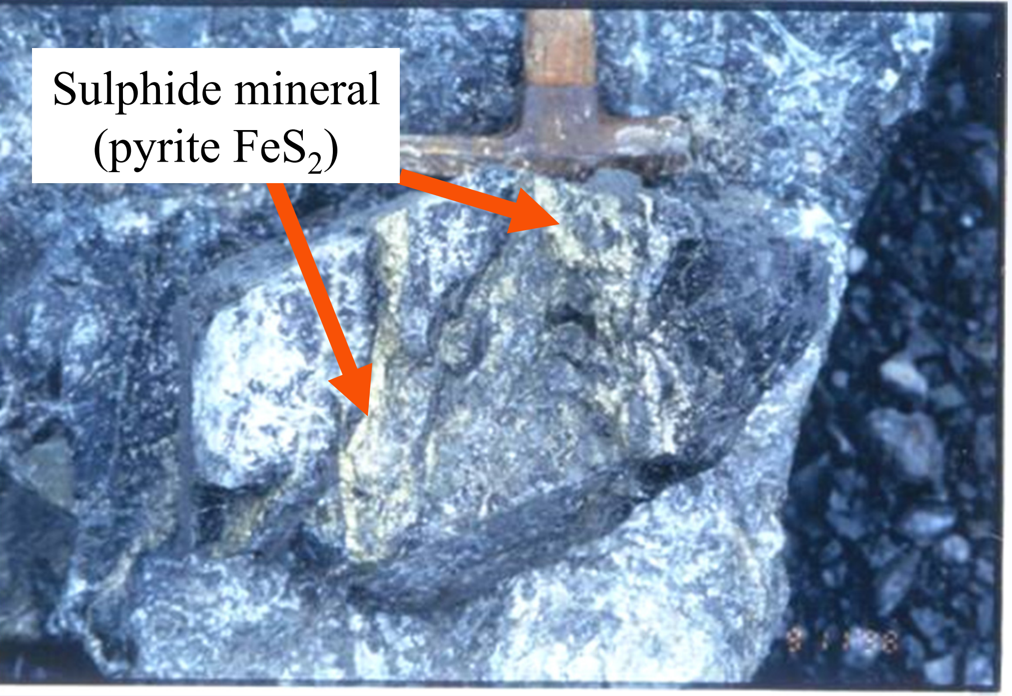
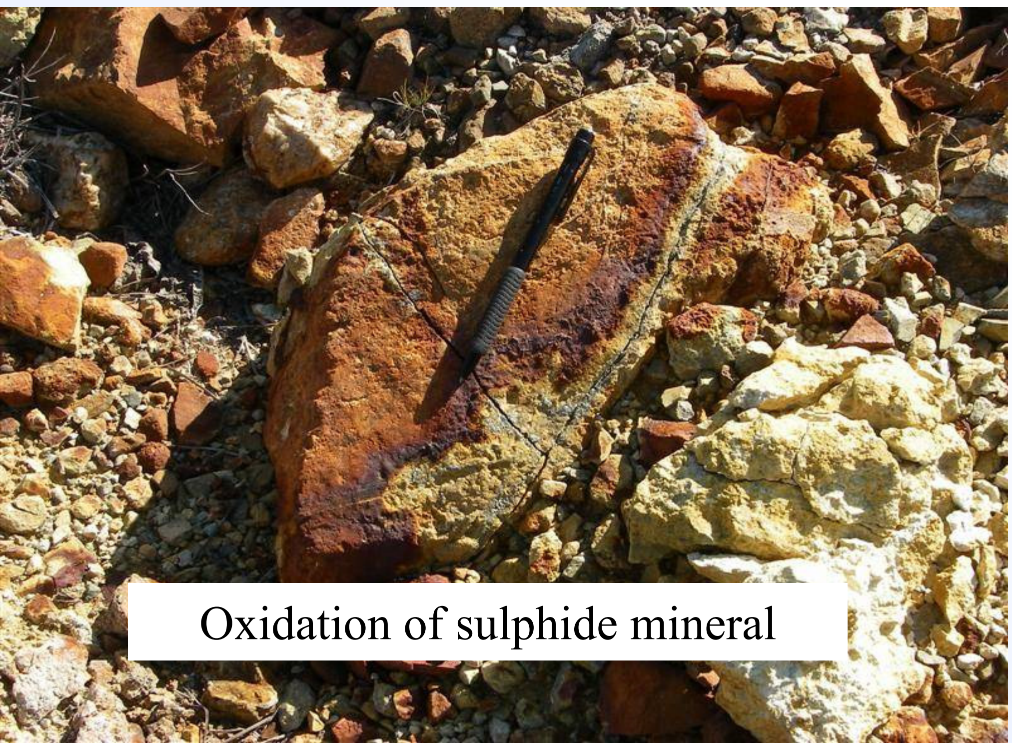
There are a number of mitigation methods for ML/ARD:

- flood,
- dry cover,
- divert groundwater,
- treat drainage and
- add NP or remove AP.

Each method:

- targets different aspects,
- uses different mechanisms and
- differs in its effectiveness, strengths and weaknesses, and associated risks.





Flooding uses the fact that most sulphide minerals are relatively insoluble.

By minimizing contact with oxygen, flooding prevents oxidation from transforming sulphides into much more soluble compounds.

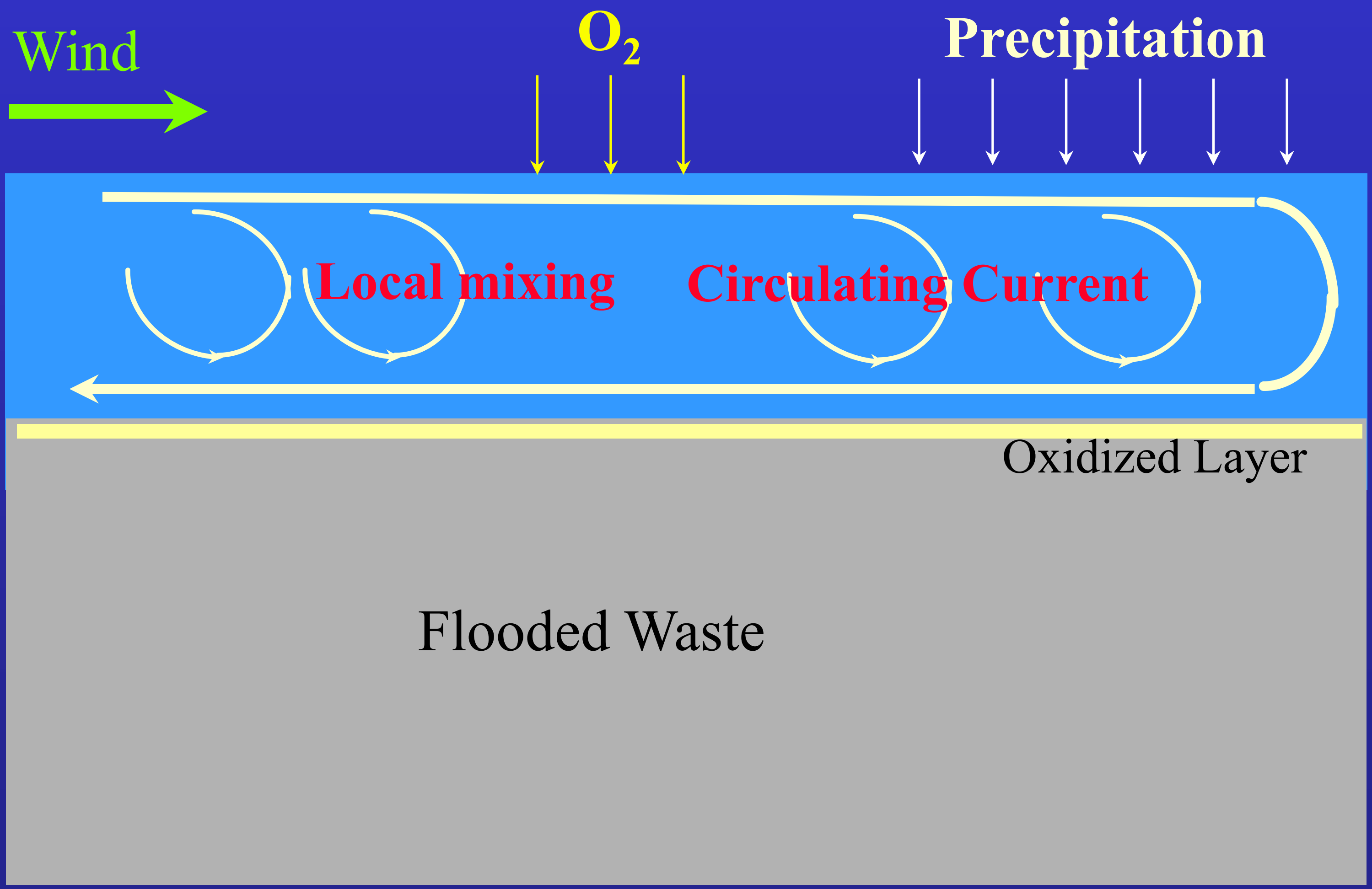
The primary mitigation mechanism in flooding is the slow movement of oxygen in the pores of flooded wastes.

Water Cover	O_2 concentration is ~ 30 times lower than air due to lower solubility (8-12 vs. 285 mg/L O_2)
Water Filled Pores in Flooded Waste	30 times lower O_2 solubility in water plus an up to 10,800 times lower migration of O_2 by molecular diffusion in water than air (20^{o}c)

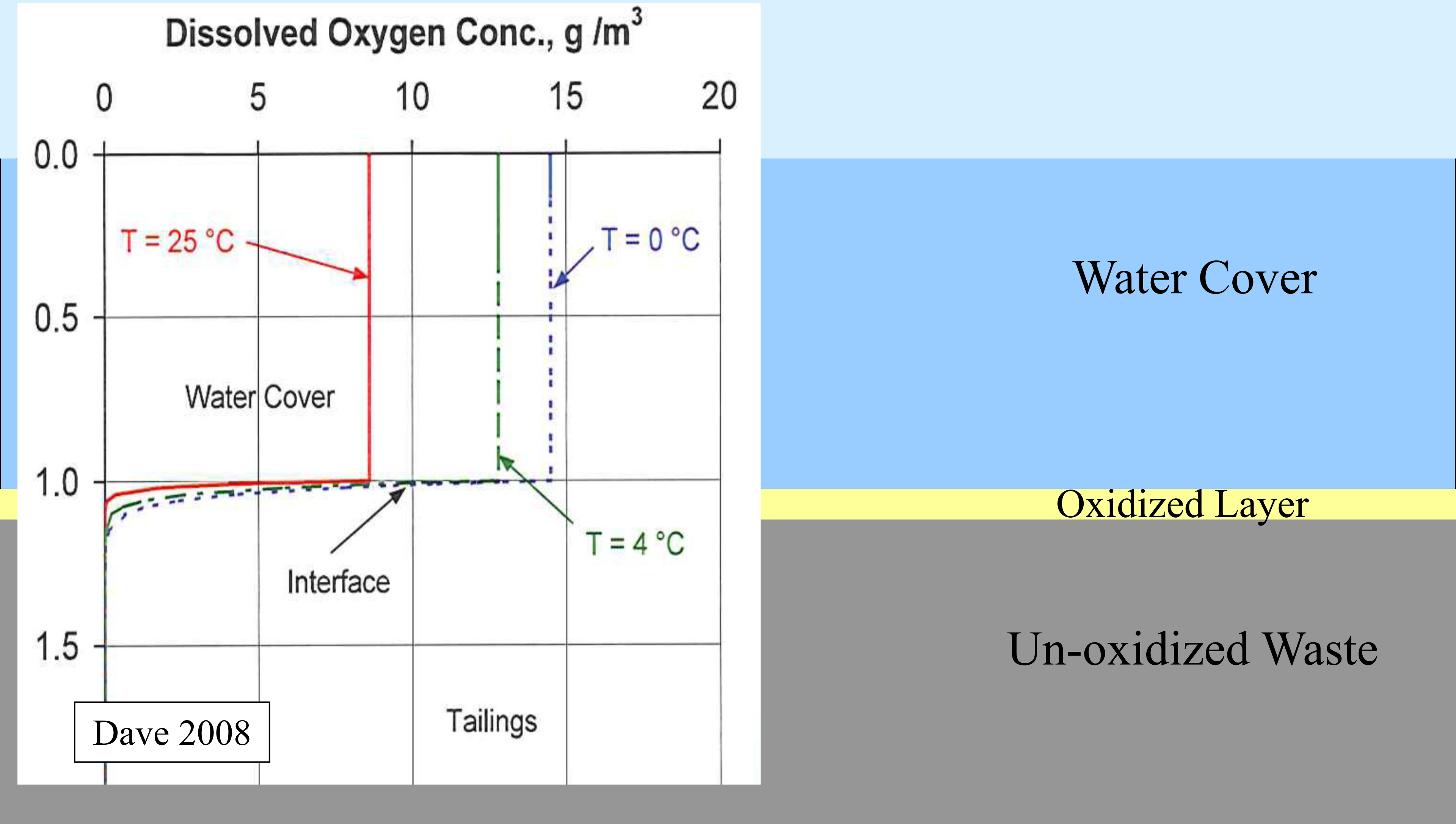
Under ideal conditions, the oxygen supply in flooded wastes is 300,000 times lower than aerial waste deposition.

Even under less ideal conditions, flooding results in a 1000 times reduction in the rate of sulphide oxidation.

Mixing by wind will result in oxygen present throughout a shallow water cover and as a result oxidation will occur at the surface of the flooded waste.



However, within the flooded waste, the rate of oxygen consumption exceeds the resupply, limiting the depth of oxygen penetration to a few millimetres to centimetres below the waste-water interface.

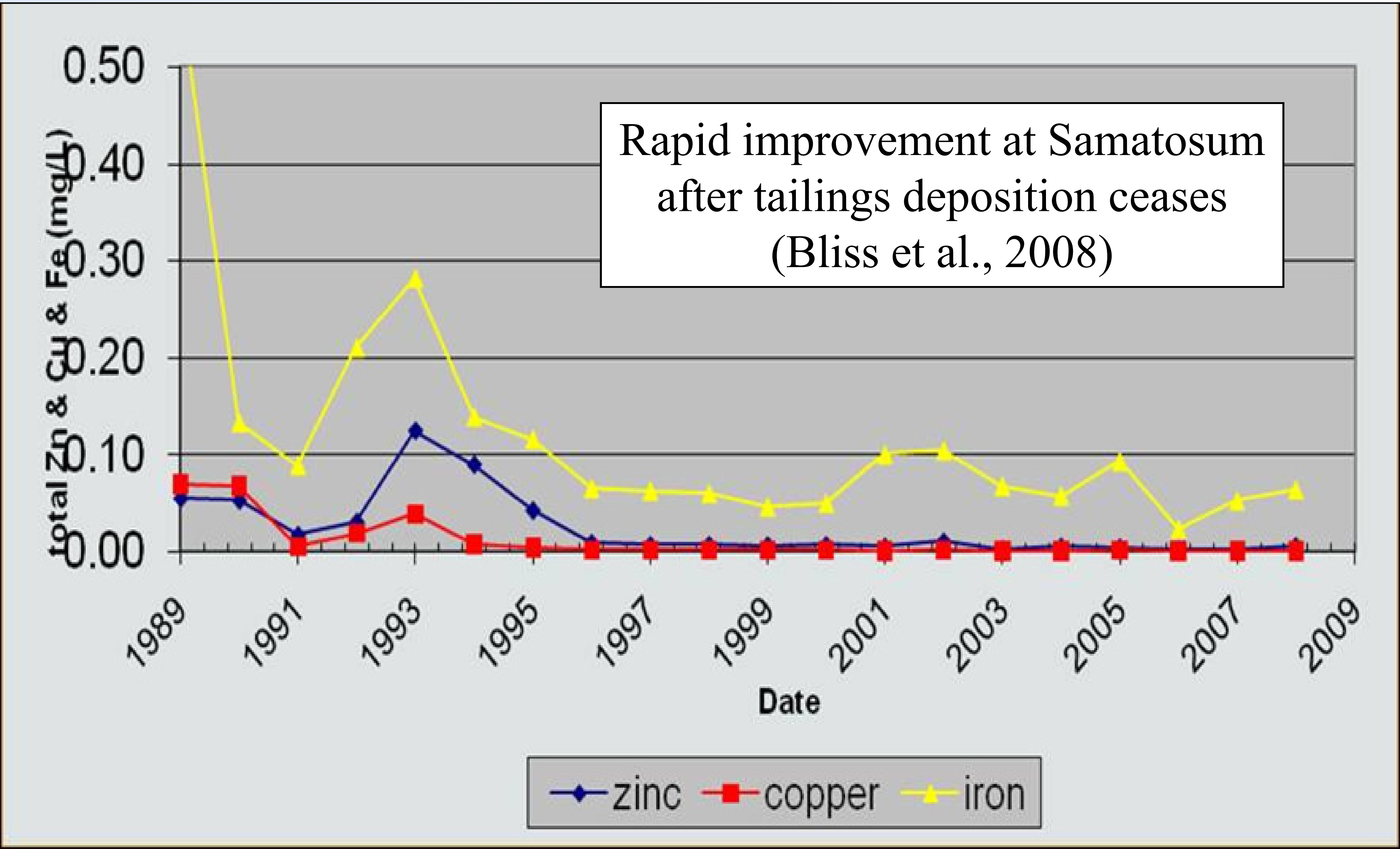


Iron released by sulphide oxidation near the waste-water interface precipitate as oxyhydroxides [$Fe(OH)_3$], which adsorb and co-precipitate trace elements (e.g., As), minimizing their release into the overlying water cover.

Below the oxidized waste-water interface, pore water may become sufficiently reducing for sulphate (SO_4) precipitation as sulphides (e.g., FeAsS), an additional sink for dissolved trace metals.

These two mechanisms may make flooded wastes a sink rather than a source for metals in the overlying water cover.

Because the rate of sulphide oxidation is so slow underwater, if wastes are flooded before oxidation can occur, the quality of the water cover quickly improves after deposition stops.

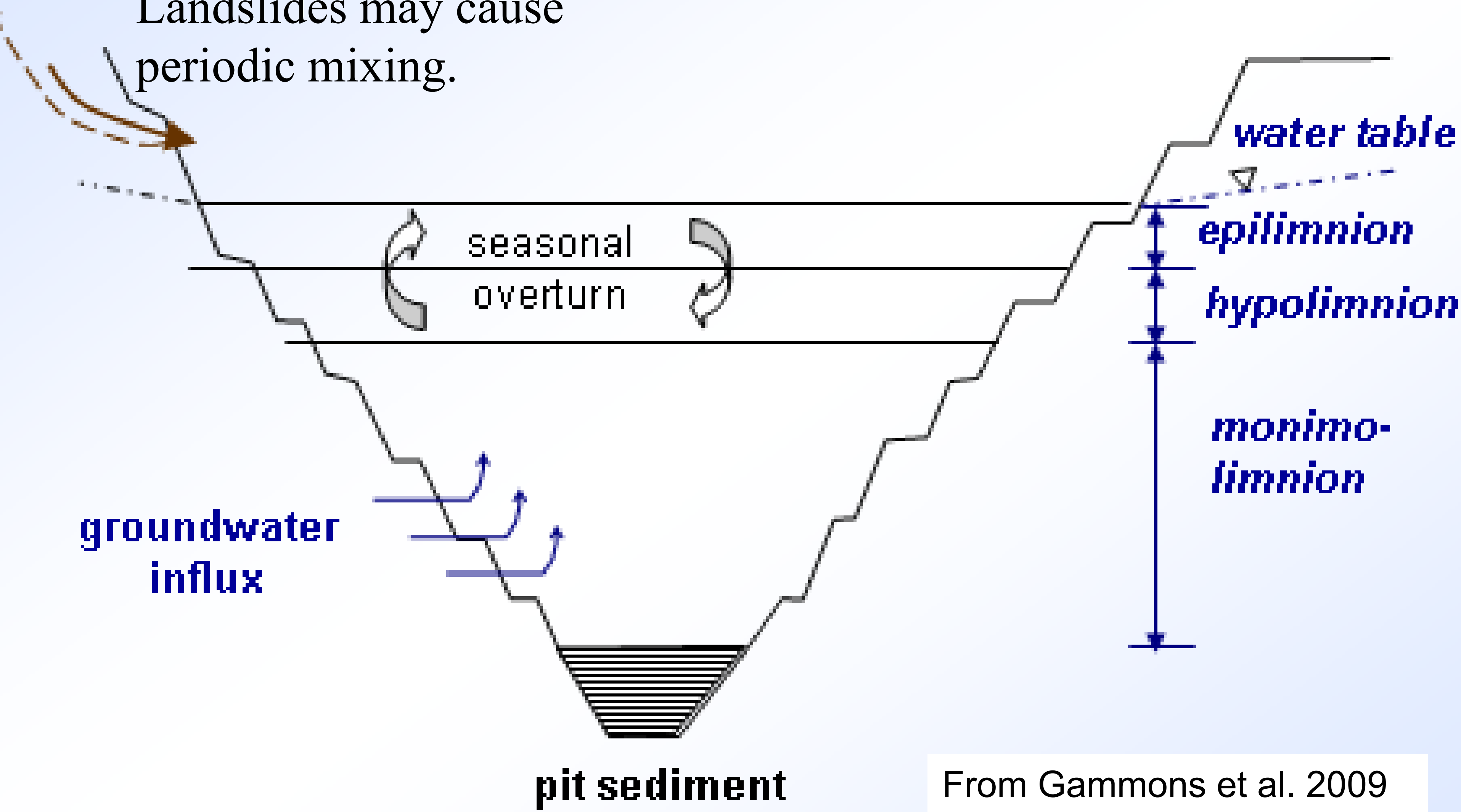


In most cases, the major source of contaminants in the water cover are sulphidic materials that are not flooded. Tailings exposed on beaches are the source of arsenic in the water cover of the Ketza impoundment.

Paktunc et al. 2011

Stratification due to temperature and salinity differences may be an additional barrier to O_2 creating sub-oxic layers in pit-lakes and underground workings that lack mixing.

Landslides may cause periodic mixing.



From Gammons et al. 2009

Design Requirements

For flooding to be sustained requires:

- a favourable water balance (drought proof); and
- an impoundment resilient to extreme floods and earthquakes.

This generally means a suitable climate, topography and construction materials for dams.

Flooding can be done:

- behind constructed dams,
- in pits or underground workings, or
- natural water bodies such as lakes.

Mines look for impoundment locations that have stable foundations and minimize dam size and ecological impacts.

Seismic conditions are also an important consideration in the design.

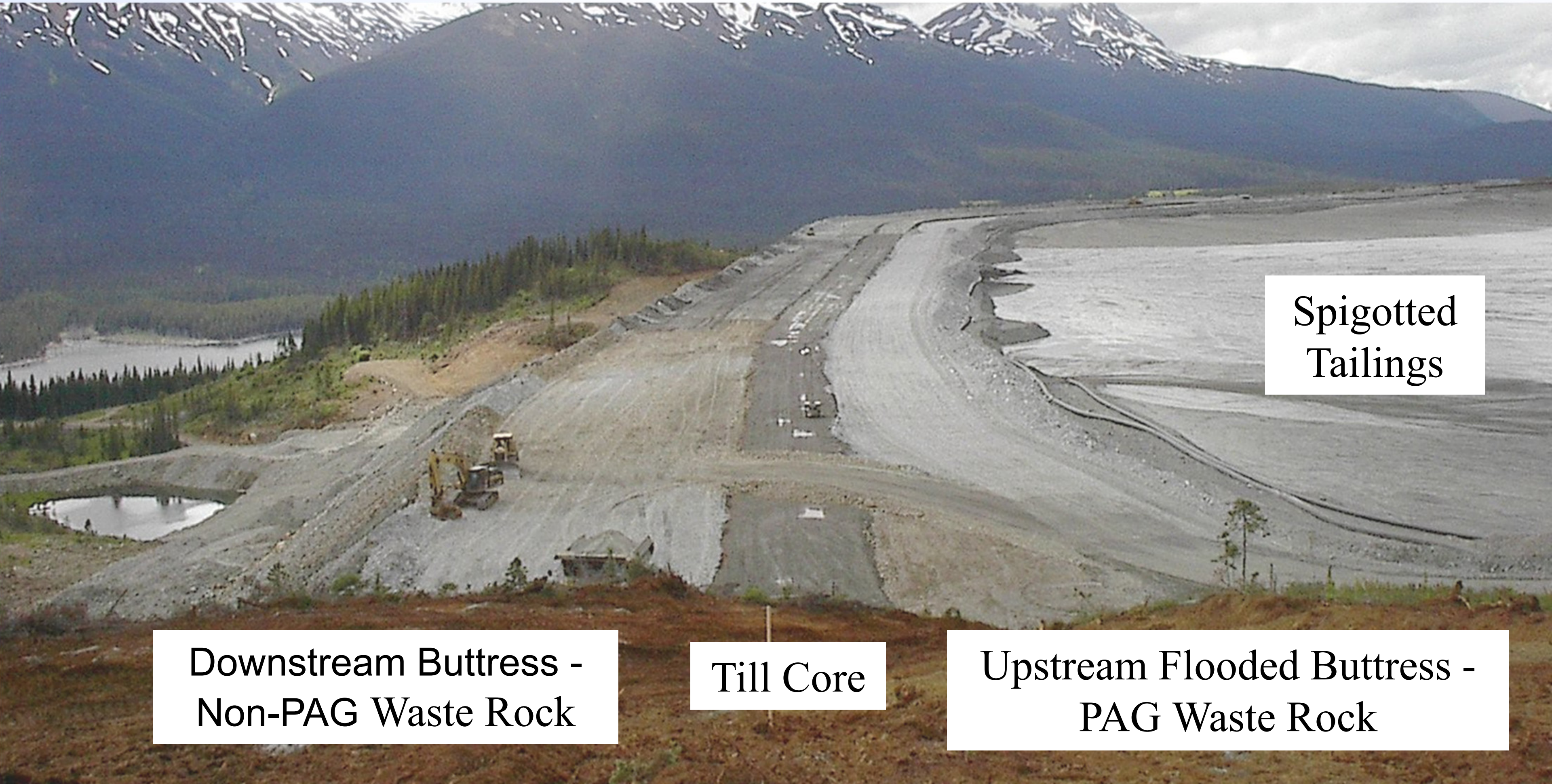
Valley impoundments, if permitted, will likely require compensation for impacts to fish-bearing water.

More dams are needed on flatter terrain away from water bodies.

Dams were needed on three sides of the impoundment at Johnny Mountain.

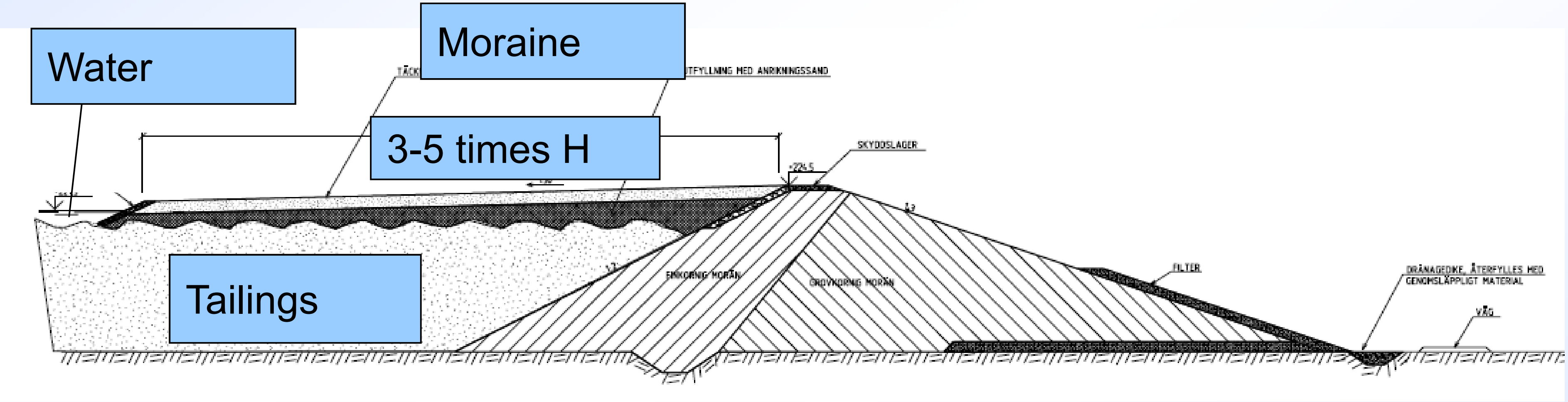
Use of mine wastes for dam construction reduces impoundment size and construction costs. At Huckleberry,

- Non-PAG waste rock was used to construct the downstream shell,
- PAG waste rock was used to construct the upstream (flooded) side,
- with an impermeable till core in middle to flood the PAG wastes.



Dams are designed to withstand possible seismic and flood events. Buttresses are one way to increase seismic stability. The downstream buttress for the till core dam at Kemess South was constructed from desulphurized cyclone tailings sand (Bent 2008).

Other measures to increase dam stability include measures to minimize erosion.



Construction of a beach upslope of the dam moves erosive wave action away from the dam and the hydraulic gradient is lowered – increasing the safety factor. Till was used as the beach material for this dam in Sweden (Lindahl 2008).

At Huckleberry, the beach to prevent wave action against the dam is constructed from desulphurized tailings and use of a pit to expand the impoundment reduced the required dam height.

Minimum Depth of Water

The water cover should be deep enough to ensure wastes remain flooded during a long drought and prevent waste movement onto beaches by wave action and ice movement.

Wave action depends on the fetch and wind speed and is difficult to predict (Yanful 2001).

Based on generic calculations of wave action, several sites have used a depth of 1 m when flooding PAG wastes.

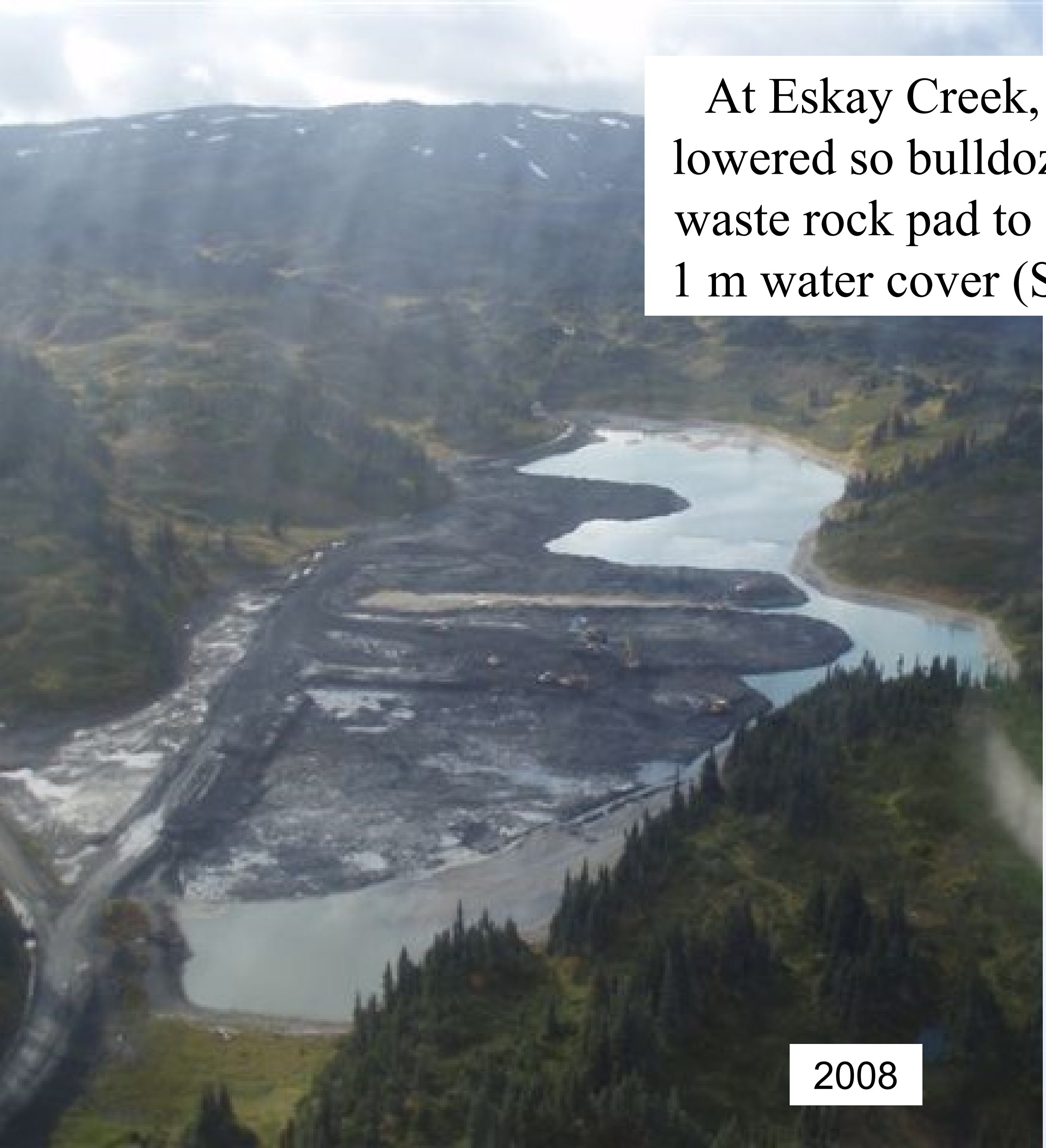
Equity Silver used ripples on the surface of flooded tailings as evidence of the depth of wave-induced tailings movement in this wide, wind-swept impoundment(Hay & Co. 1996).

Bed movement was observed up to a depth of 1.4 m.

As a result, the minimum depth of the water cover was increased to 1.7 m.

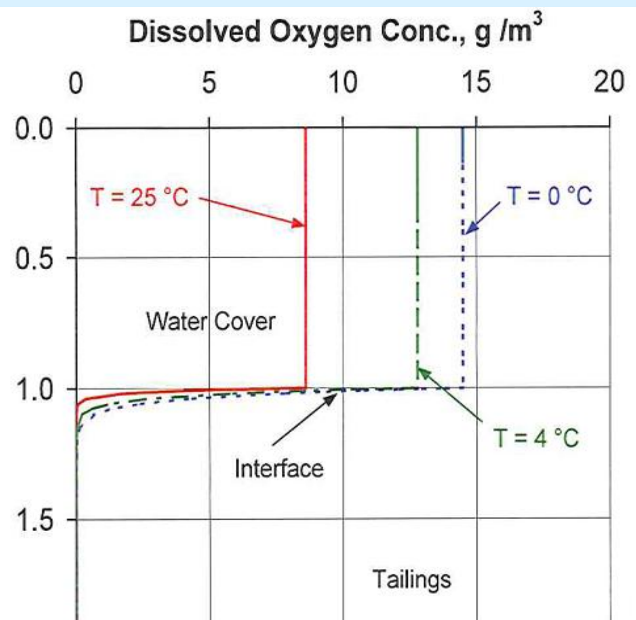
Water pressure or dredging can be used to lower the height of tailings to achieve a minimum depth for the water cover.

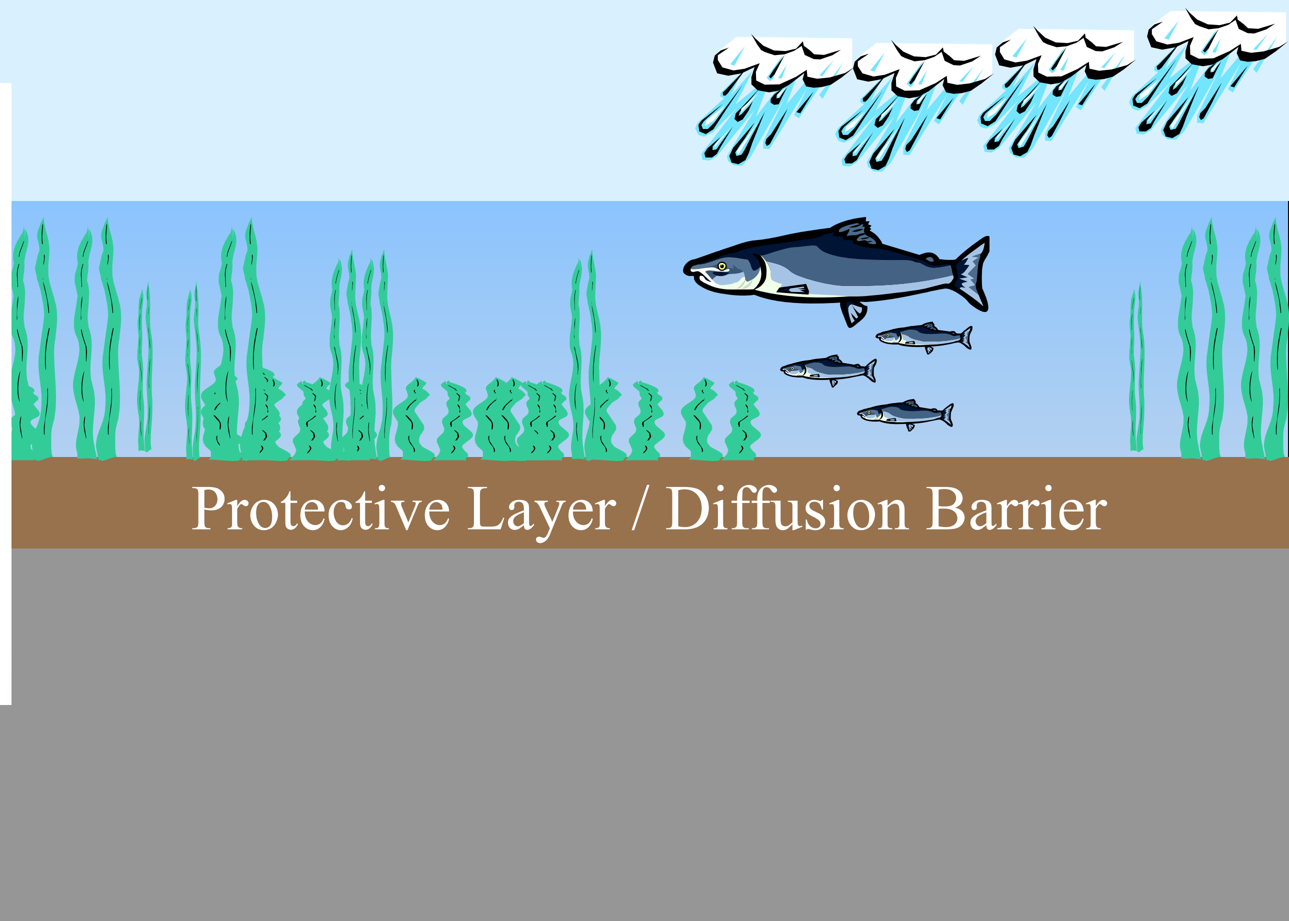
At Eskay Creek, the lake level was lowered so bulldozers could lower the waste rock pad to achieve a minimum 1 m water cover (Sibbick et al. 2011).



Natural sedimentation or placement of a protective layer or ‘diffusion barrier’ on top of the flooded waste can minimize or prevent:

- downward diffusion of oxygen into the underlying wastes,
- upward diffusion of soluble contaminants into the water cover and
- isolate the flooded waste from invading biota.

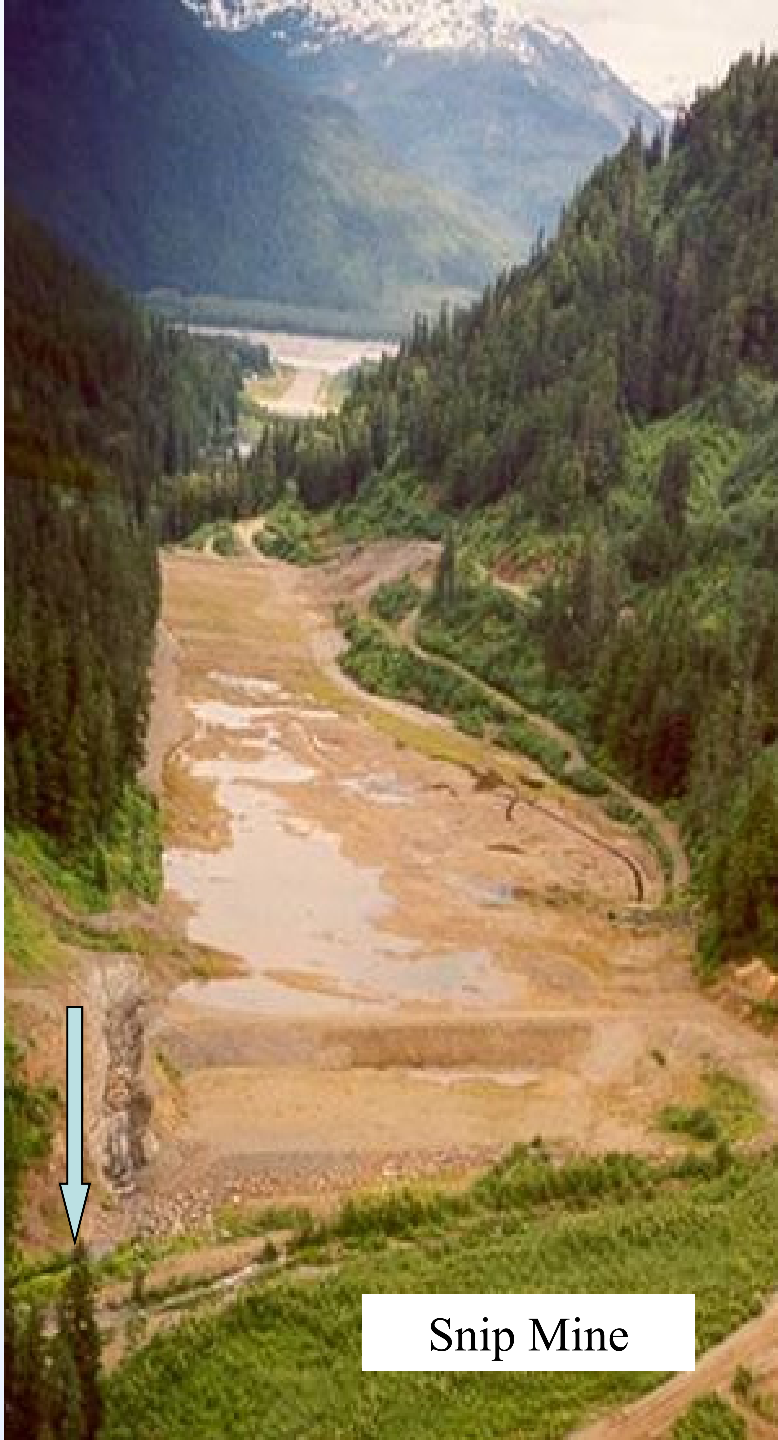




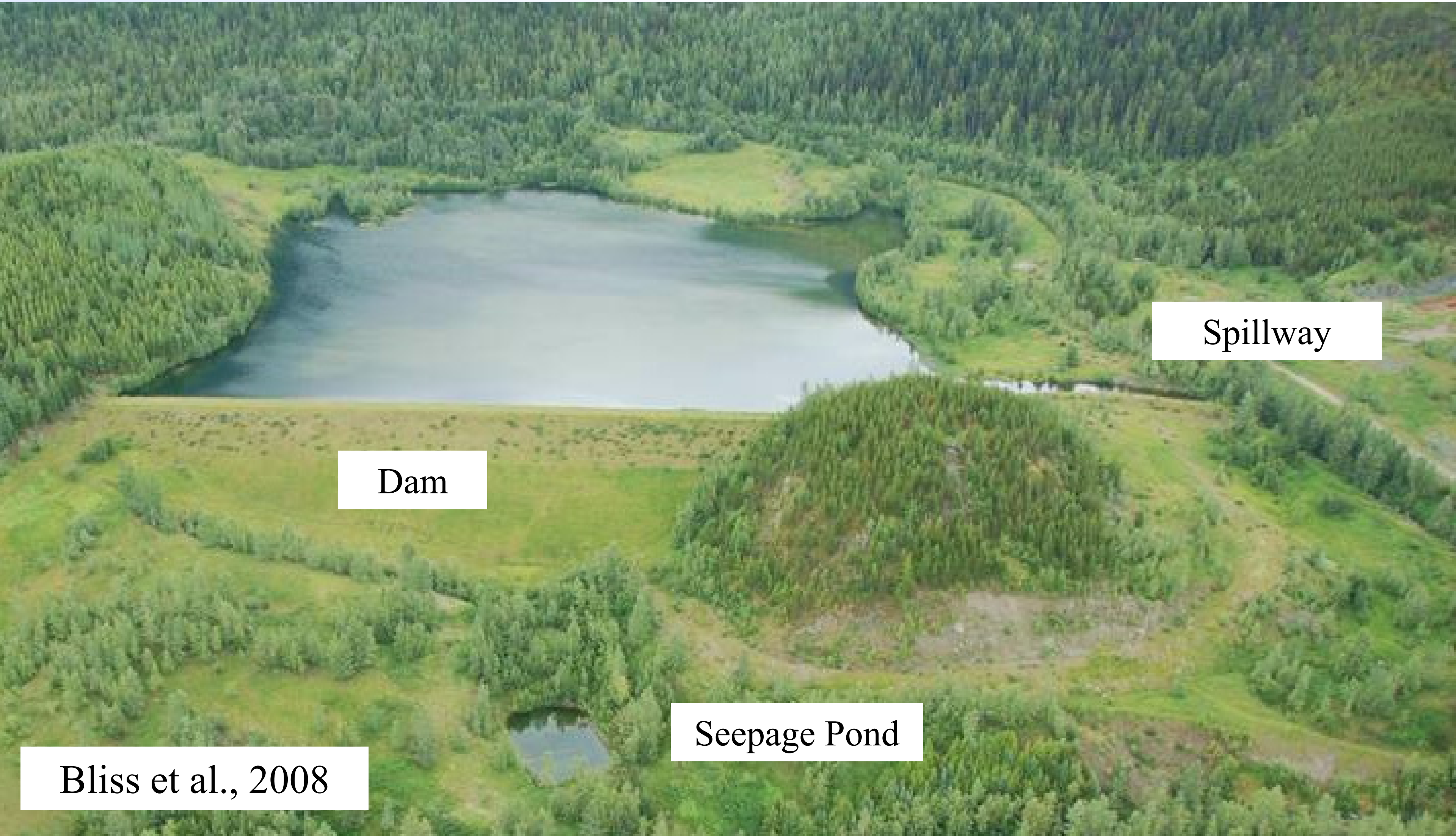
Snip placed a soil cover on top of flooded tailings.

Although water storage in the impoundment is small, the soil cover remains saturated because high precipitation and runoff from surrounding slopes creates a positive water balance throughout the year.

Spillways are usually constructed in bedrock adjacent to the dam.



A spillway must be big enough for the probable maximum flood (pmf). The pmf will depend on the size of the contributing watershed and changes in precipitation due to climate change.

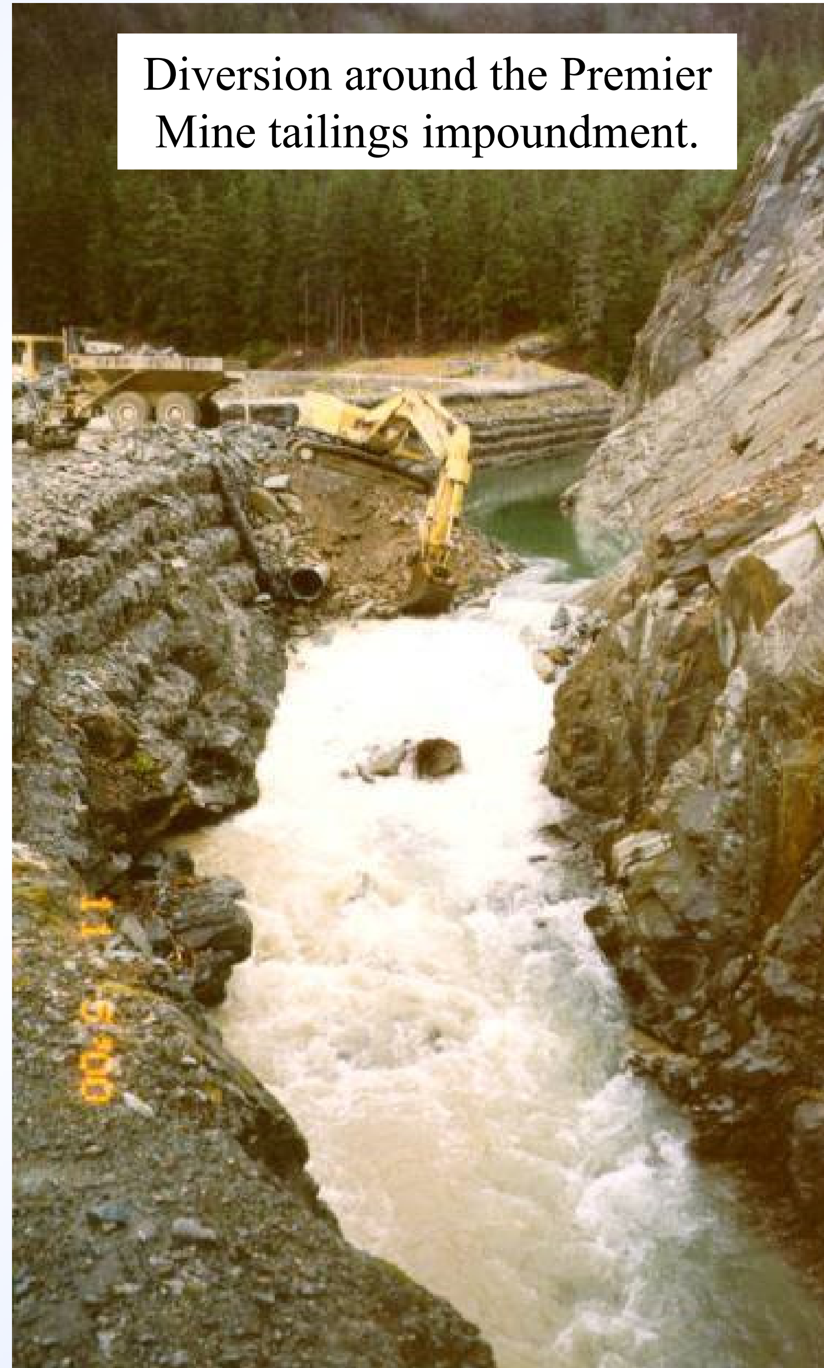


Other water management issues:

- maintaining adequate flow for fish downstream of the impoundment,
- conducting flow across or around the impoundment and
- collecting dam seepage.

Potential benefits of stream flow through an impoundment include maintaining aeration during the winter.

Diversion is usually required to maintain adequate freeboard during mining because the spillway is not constructed or functional until the dam reaches its final height.



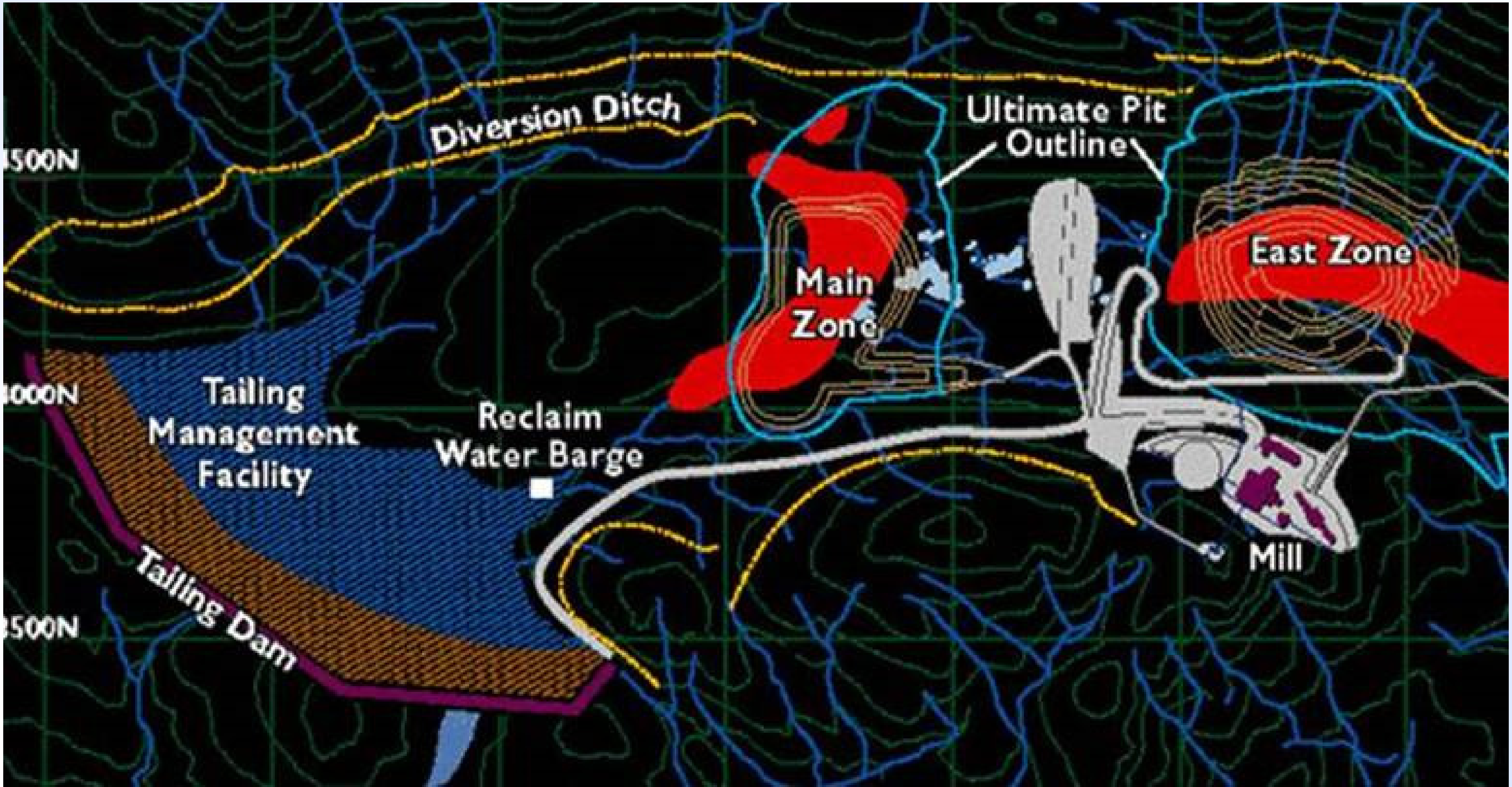
Diversion around the Premier Mine tailings impoundment.


During operation, dam seepage is monitored and if necessary pumped back into the impoundment.
Seepage Collection Ponds

Flooded Wastes and Flooding Wastes

Information about the geochemical composition and drainage chemistry of the flooded waste is required to determine soluble constituents, potential drainage chemistry and when flooding must occur.

A delay in flooding may be problematic if oxidation prior to flooding produces a large load of soluble metals.

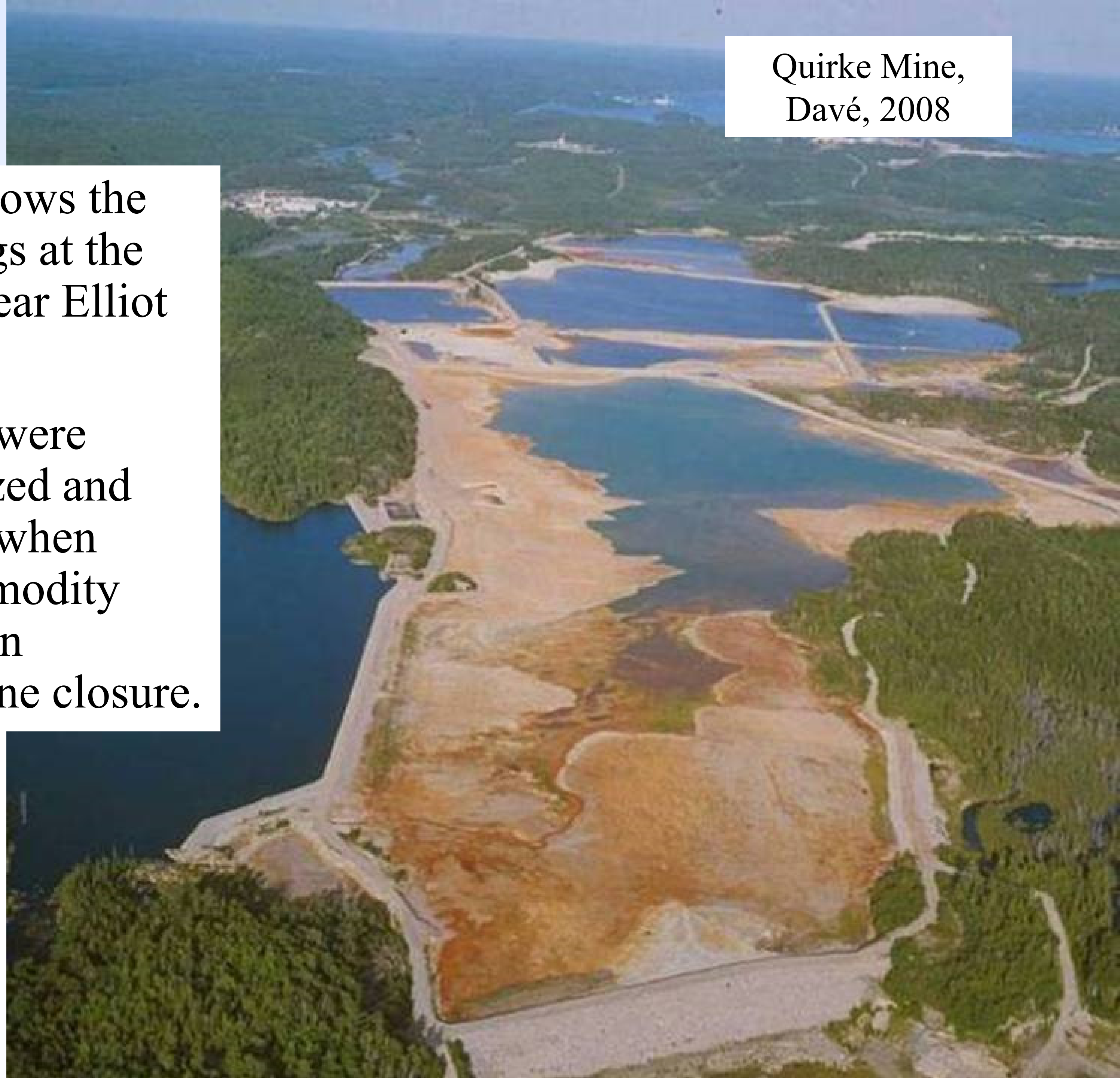


Measures to prevent ARD onset in PAG waste prior to flooding:

- monitoring AP and NP to ensure adequate NP in exposed waste,
- minimizing the height of waste above flood water,
- an ability to breach diversions if accelerated flooding is required,
- having sufficient financial security to move exposed wastes to a flooded location if accelerated flooding is required and
- monitoring the decline in NP in exposed wastes.

This picture shows the uranium tailings at the Quirke mine near Elliot Lake.

These tailings were partially oxidized and already acidic when changing commodity costs resulted in unexpected mine closure.

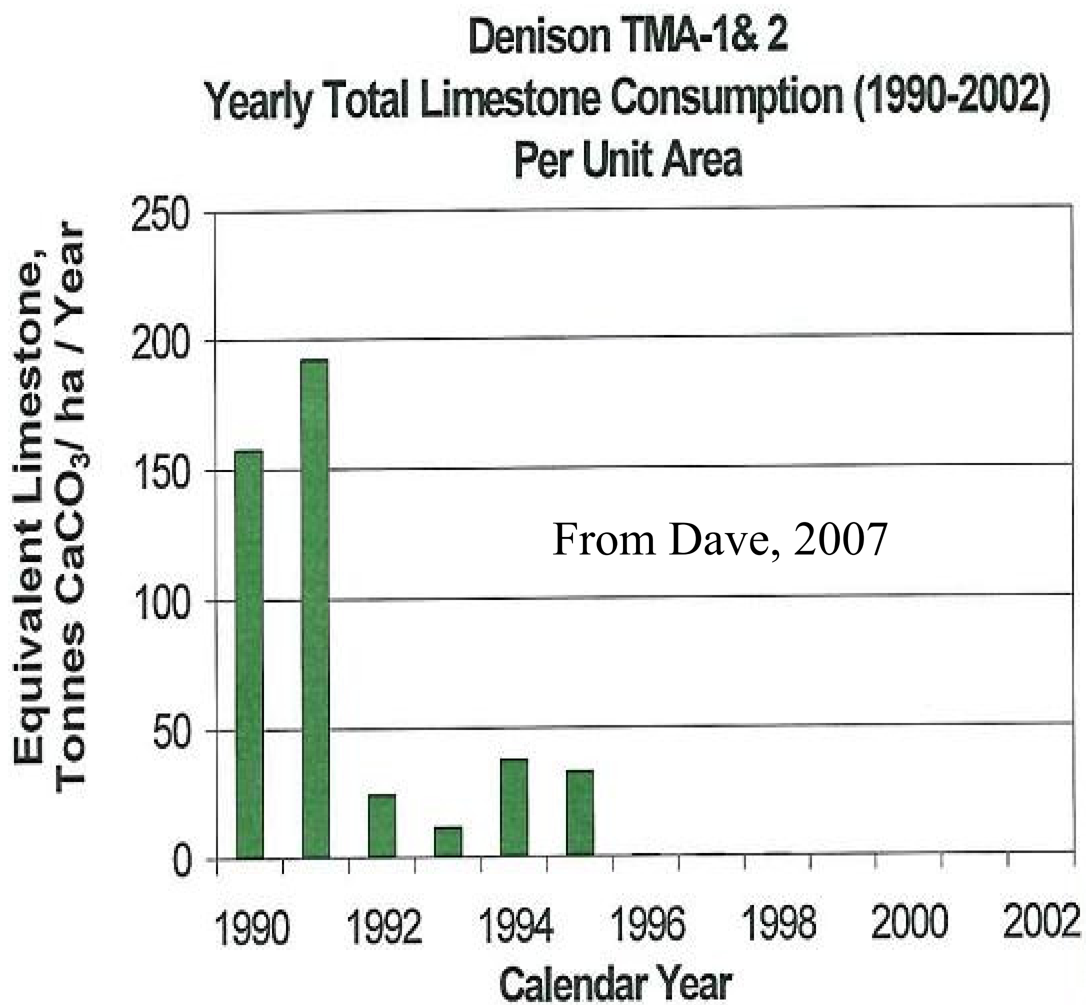


Quirke Mine,
Davé, 2008

Flooding these already acidic tailings minimized further oxidation but accelerated leaching of existing oxidation products. Limestone was mixed into the surface prior to flooding to reduce contaminant release and the impoundment drainage is treated with lime prior to discharge.

Lime costs for treating the discharge were high in the first two years, decreased greatly in year 3, and have been minimal since year 7.

Year	Total $CaCO_3$ Equivalent (tonnes/year)	Total $CaCO_3$ Equivalent (tonnes/ha/year)
1990	42,779	157.858
1991	52,119	192.320
1992	6,636	24.487
1993	3,201	11.813
1994	10,288	37.963
1995	9,024	33.300
1996	74	0.275
1997	59	0.218
1998	18	0.065
1999	1	0.002
2000	1	0.002
2001	2	0.006
2002	0.16	0.001



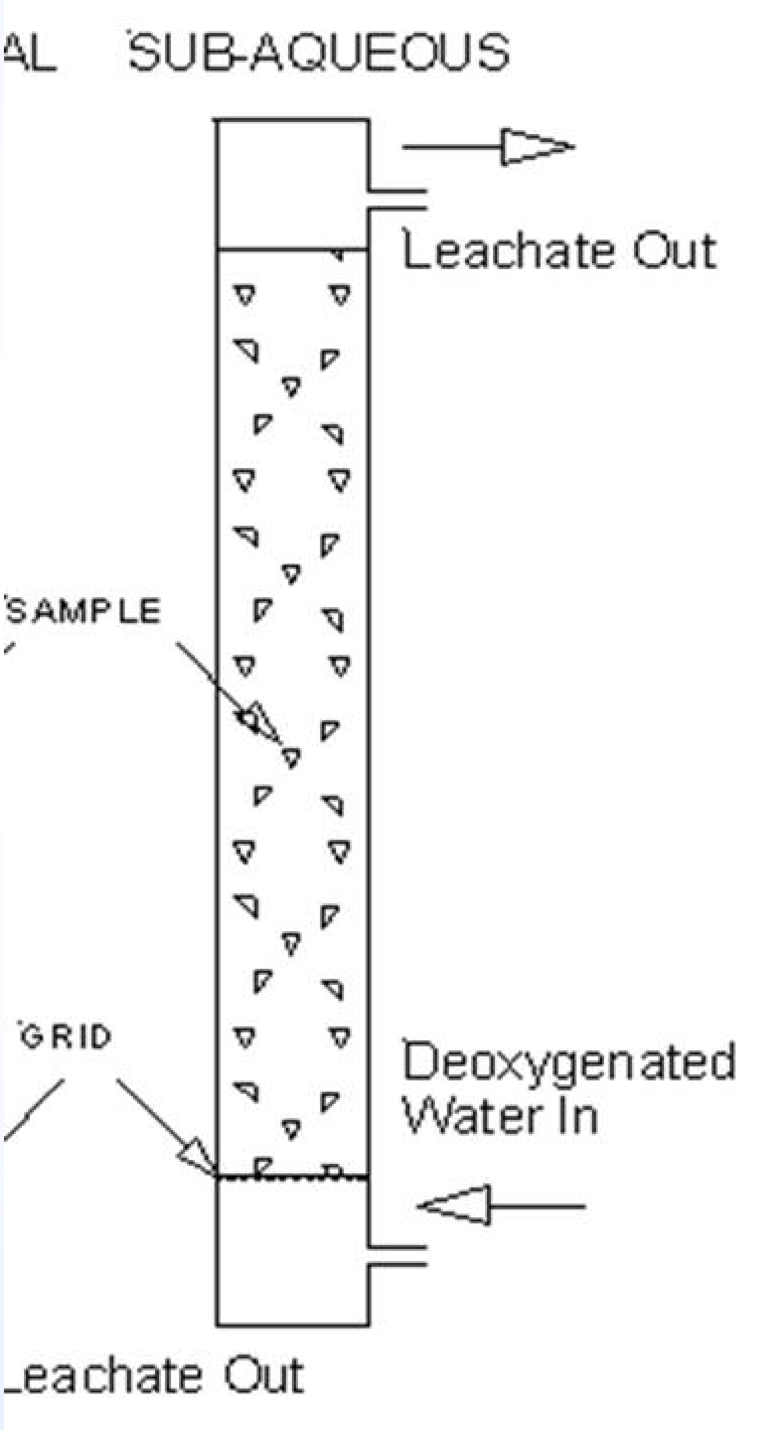
The East Sullivan Mine placed a > 2 m wood waste cover over oxidized tailings it planned to flood.

Decomposition of the wood consumes oxygen and has created strongly reducing conditions in the underlying tailings.

Reducing reactions precipitate metals as sulphides and create alkalinity that neutralizes acid in the previously oxidized tailings (Germain et al. 2009).

Shake flask analysis and columns can be used to predict acid and contaminant release when wastes are flooded.

Shake flask results were used to predict the lime rate needed for neutralization of oxidized waste rock flooded at Sulphurets (Price 2005).



Other Inputs that Impact the Chemistry of a Water Cover

Flooded waste facilities may be used to store materials, in addition to tailings and waste rock, that may impact future drainage chemistry.

These include:

- chemicals use in processing ore, such as cyanide,
- by-products of processing, such as thiosalts,
- waste products of drainage treatment and
- site drainage that is unfit to discharge.

It is therefore important to keep a careful record of everything that goes into the impoundment.

Thiosalts

Acid generating intermediate sulphur species (such as elemental sulphur and thiosalts) may be produced during processing high sulphide ore. Thiosalts are a problem at a number of mines in Eastern Canada.

$$S_2O_3^{2-} + 2O_2 + H_2O \rightarrow 2SO_4^{2-} + 2H^+$$

Thiosalts are preserved under cold temperatures. Oxidation and acid production occur when temperatures rise have been responsible for acidification in tailings impoundments or in the receiving environment after spring discharge at a number of mines.

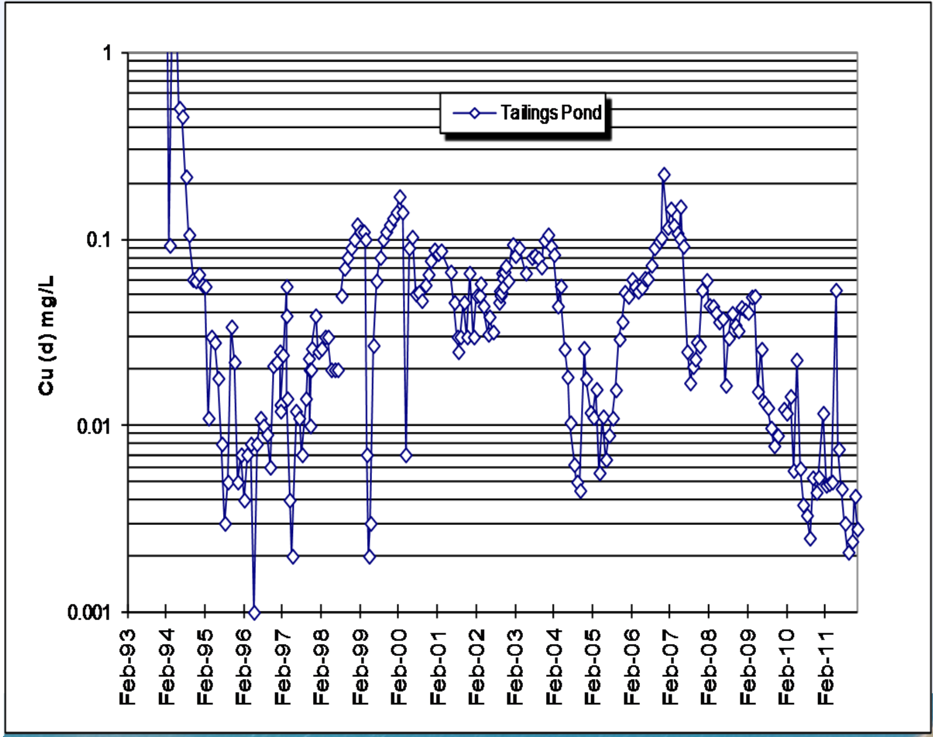
Cormier 2010

Flooded impoundments are often a contingency storage location for drainage a site cannot discharge.

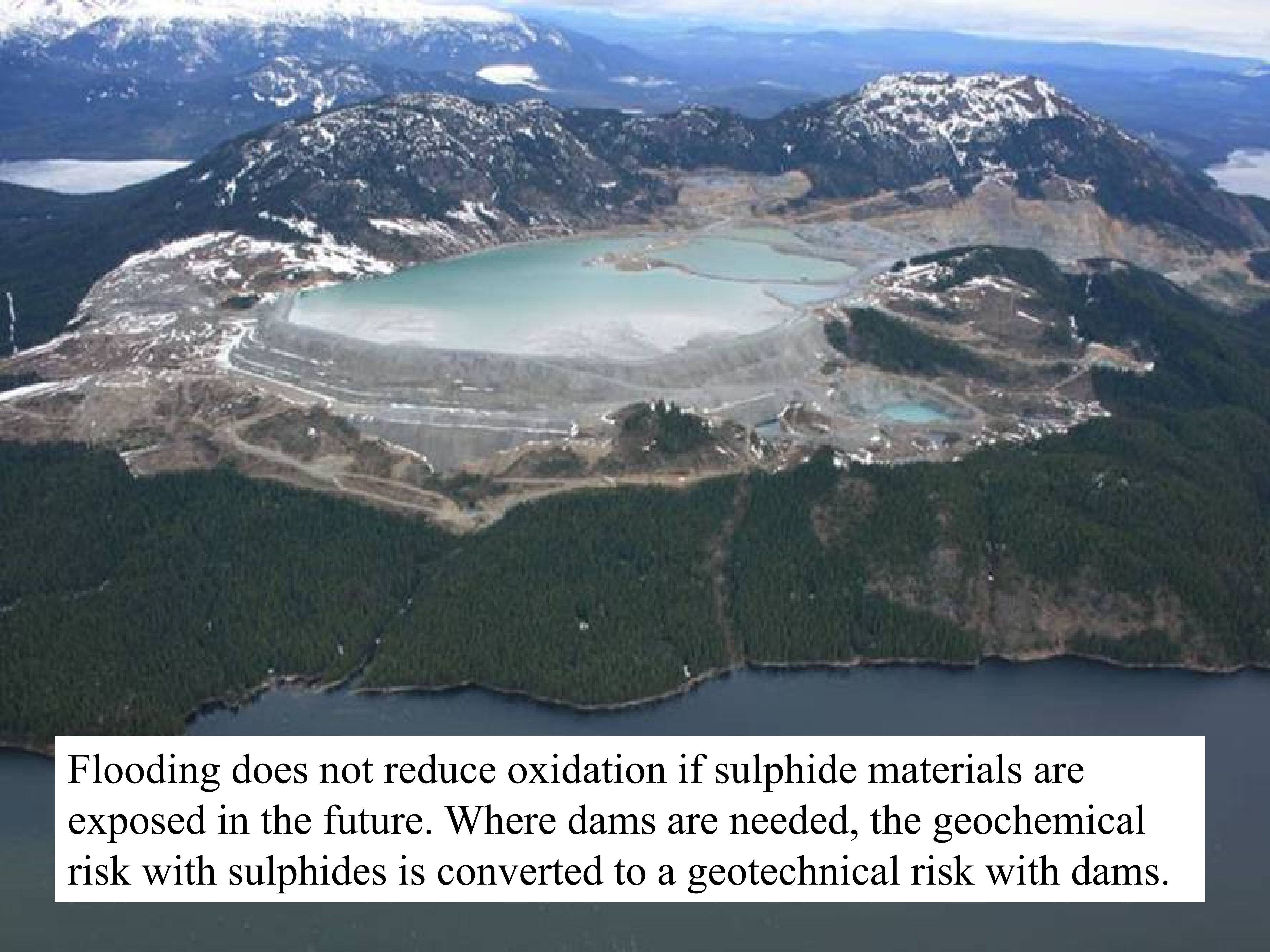
During mining at Equity Silver , ARD from one of the dams was pumped into the impoundment and neutralized by alkalinity in the process water.

When the water cover pH in the impoundment decreased several years after mine closure, Cu started to increase.

The source of Cu appears to be pH sensitive hydroxides [$Cu(OH)_2$] created (precipitated) from the ARD pumped into the impoundment.

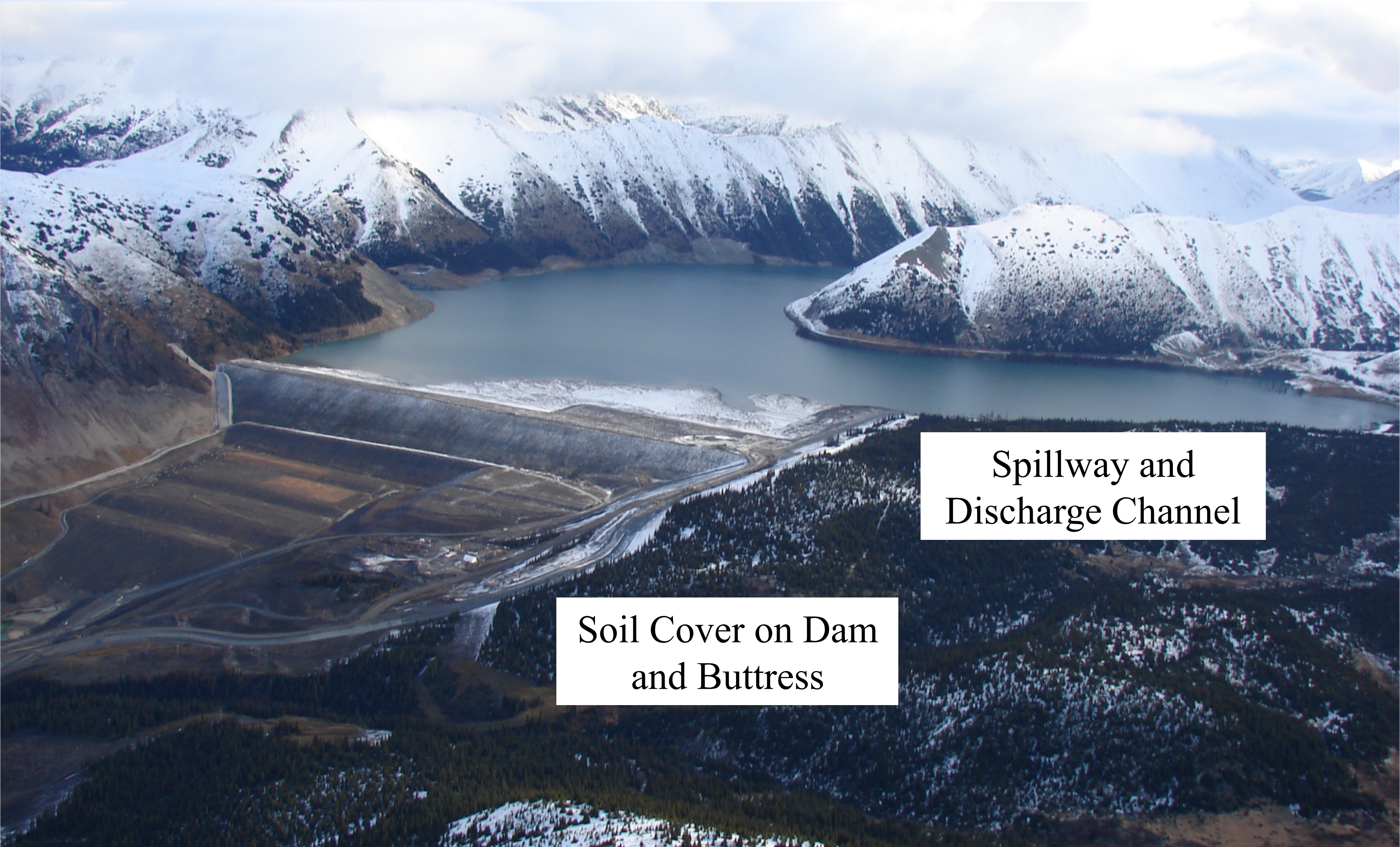


Perpetual Monitoring and Maintenance



Flooding does not reduce oxidation if sulphide materials are exposed in the future. Where dams are needed, the geochemical risk with sulphides is converted to a geotechnical risk with dams.

Post-closure monitoring and proactive maintenance are essential to ensure impoundments continue to flood mine wastes.



Regular inspection and periodic maintenance and repair are needed to prevent erosion. Erosion may result from damage to the vegetative cover by disease, forest fires, burrowing wildlife and over-grazing.

Bliss et al. 2008

Ice jams may also be a periodic concern.

One of the most important maintenance concerns is beaver dams, which may:

- change drainage inputs,
- block the spillway,
- flood dam foundations and
- break releasing an even larger flow during a flood event.

The photo below is from the Matachewan tailings spill, when water overtopped the tailings dam after a beaver dam plugged up the spillway.

Strategies for managing beaver include:

- frequent inspection,
- trapping,
- removal of dams and
- measures to prevent dam construction.

Boulders were placed in the spillway at Snip to prevent beaver dams (Price 2005).

Fourteen years later, beaver plugged the front of the boulder-filled spillway with leaves and mud.

The mine now has to periodically remove beaver dams.

Impoundments Without Perpetual Monitoring and Maintenance

Mines can avoid the cost and maintenance associated with dams by backfilling materials into eventually flooded mine workings.

Perpetual maintenance of dams may also be avoided by deposition in lakes. Buttle Lake is one of many British Columbia fish-bearing lakes with previous tailings deposition.

Buttle Lake
Photo by Frank Gerdes.

Disposal of waste rock and tailings in an alpine lake at Eskay Creek was permitted because there were no fish in the lake and large dilution downstream prior to fish-bearing water.

British Columbia also has several sites with submarine tailings disposal.

Alice Arm was the site of tailings deposition from the Kitsault Mine from 1965-1972 and 1981-1983.

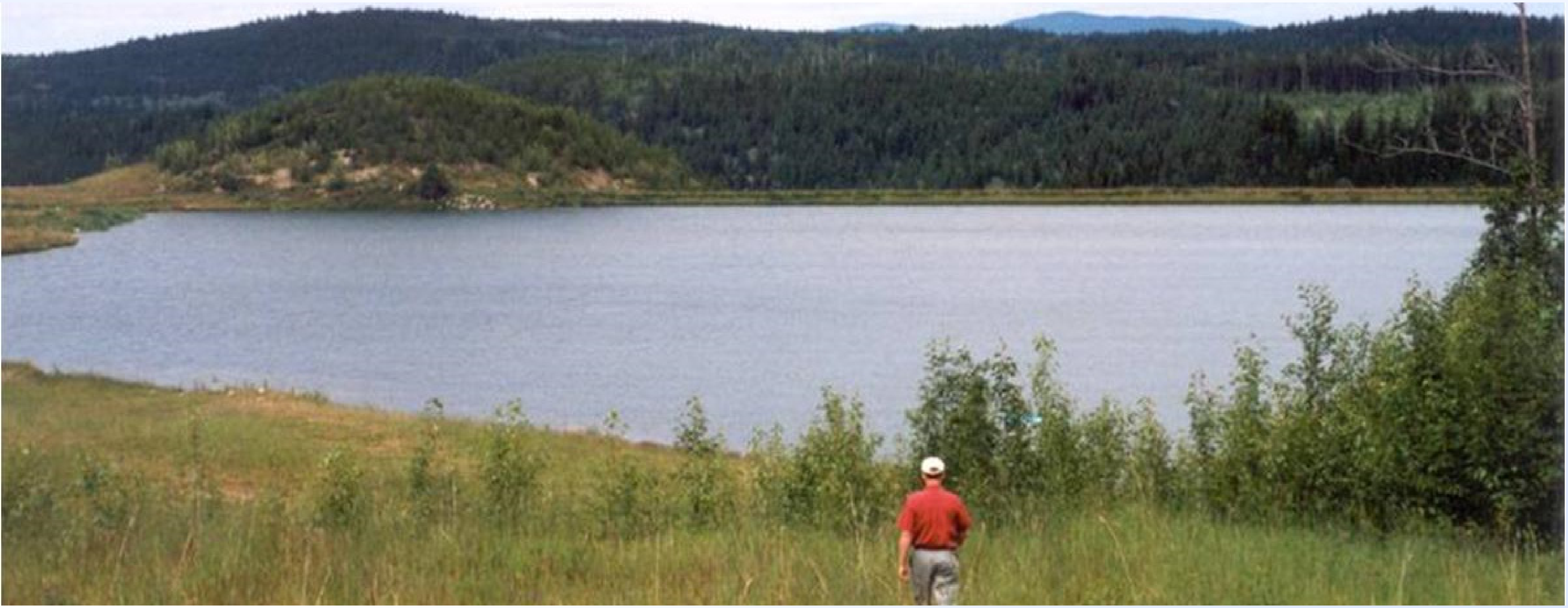
Conclusions

Like most forms of mitigation, the long-term record with flooded mine wastes is limited. Features that deserve further study are:

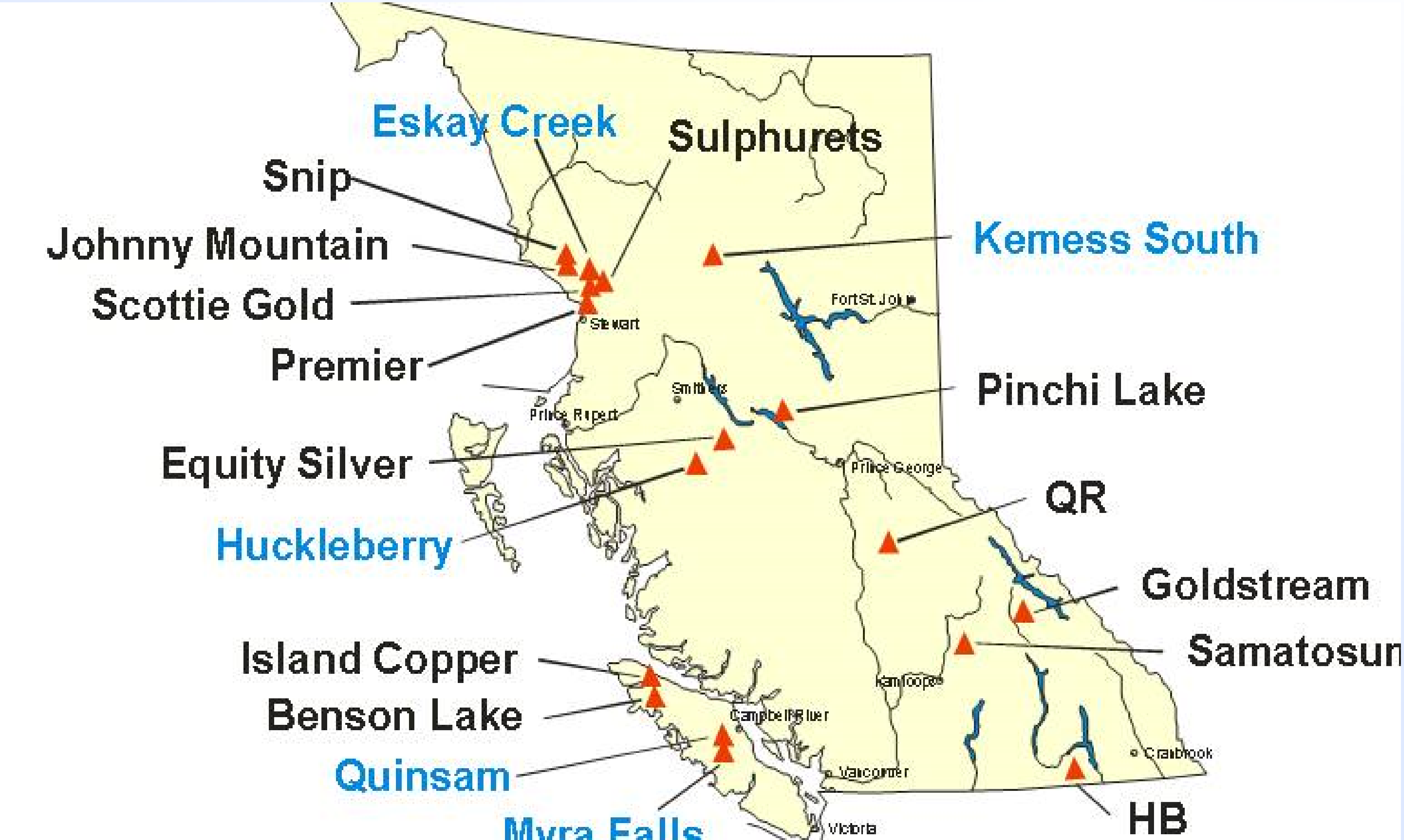
- how to ensure perpetual maintenance,
- oxidation and metal fluxes from flooded waste rock,
- ecological health and productivity when nature reasserts itself and
- the fate of treatment sludge co-disposed with tailings.

Dave 2011

- Advantages of flooding are the almost complete prevention of sulphide oxidation and the relatively minor closure costs of maintaining dams and other water management features.
- If there are favourable site conditions, flooding may be the most cost-effective mitigation strategy.
- However, there are a number of challenges.
- A constructed impoundment has a number of post-closure management issues including the long-term requirement for dam and spillway maintenance.



Many British Columbia mines use flooding. However, some jurisdictions prohibit or discourage flooded impoundments due to past failure of poorly built dams (West Virginia) or belief that other forms of mitigation provide lower long-term risk and liability (Quebec).



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HB Mine