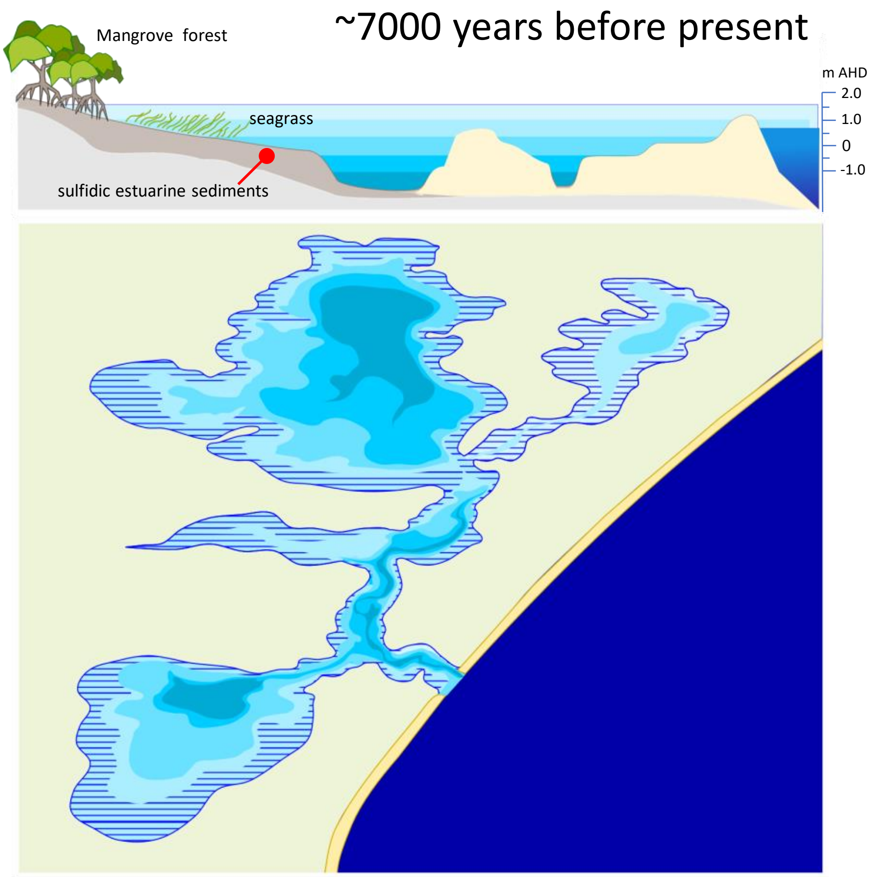
Lake Cathie and Lake Innes – unique systems under stress

Lake Innes and parts of Lake Cathie are reserved as part of Lake Innes Nature Reserve to protect and conserve outstanding unique or representative ecosystems, species, communities and natural phenomena. They are currently under extreme stress due to drainage modifications that are exacerbating the creation and disturbance of acid sulfate soils.



How the lakes formed

Rising sea-levels

Lake Cathie and Lake Innes formed at the end of the last ice age, when rising sea levels inundated natural depressions in the landscape.

Salty at the start

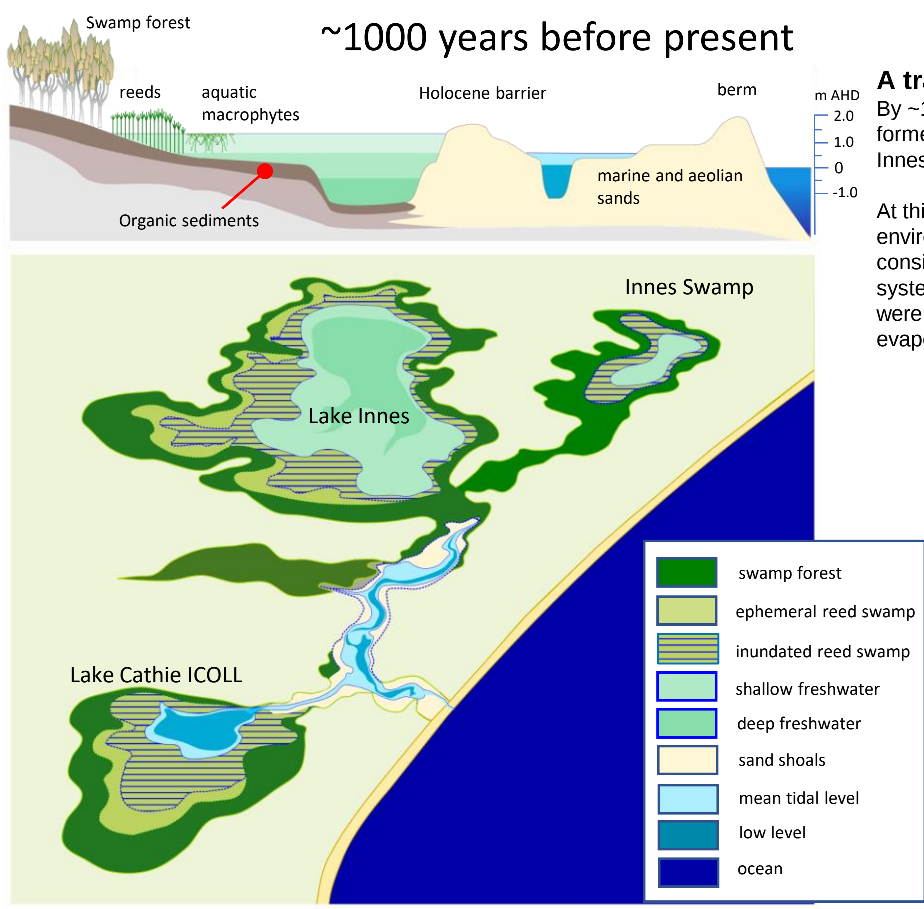
When sea levels stopped rising (about 7000 years ago), they were slightly higher than today. Both Lake Cathie and Lake Innes were open to the ocean, and were saline and deeper than today. However, at this point, both lake systems began to slowly infill with sediment from the land and sea.

As the lake systems filled with sediment, the shallow margins of both lakes were colonised by mangroves and saltmarsh. Both lakes became shallow estuarine backwaters with high rates of organic matter accumulation.

A precursor to acid

These conditions of abundant organic matter, plenty of sulfate from the sea, plus a settled environment – were ideal for bacteria to undertake sulfate reduction and form pyrite (FeS_2) in the lake sediments .

Sediment that are rich in pyrite and other iron sulfides (known as‘‘sulfidic sediments’’) are very important because they are precursors to acid sulfate soils (ASS).



A transition to freshwater

By ~1000 years ago, infilling processes had formed a natural barrier which separated Lake Innes and Innes Swamp from Lake Cathie.

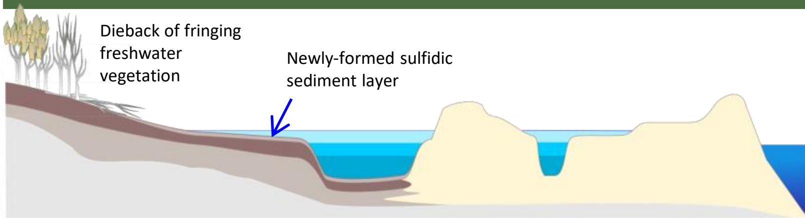
At this point, Lake Innes became a freshwater environment with water levels perched considerably higher than the Lake Cathie system. Variations in Lake Innes water levels were then driven by natural rainfall and evaporation.

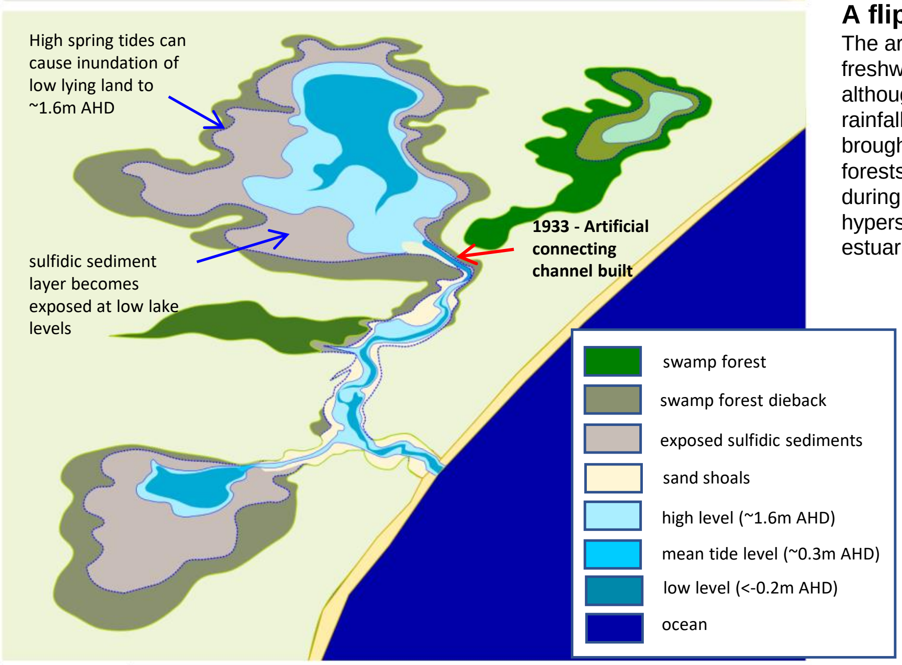
A big freshwater swamp

The freshwater Lake Innes became the largest freshwater lake / swamp environment in coastal NSW. Shallow lake margins were colonised by swamp forests, freshwater reeds and aquatic macrophytes. Sediment profiles indicate high rates of productivity and organic matter accumulation.

The sulfidic sediments formed during the previous estuarine / saline phase were largely buried under the new freshwater organic sediment accumulations.

The current state of Lake Cathie and Lake Innes





Artificial drainage?:

In 1933 an artificial connection was made between the lakes. The intention was to drain Lake Innes for agricultural production. This proved impossible because in many places the lake bed was below sea-level and far too low for effective drainage.

A flip back to salty:

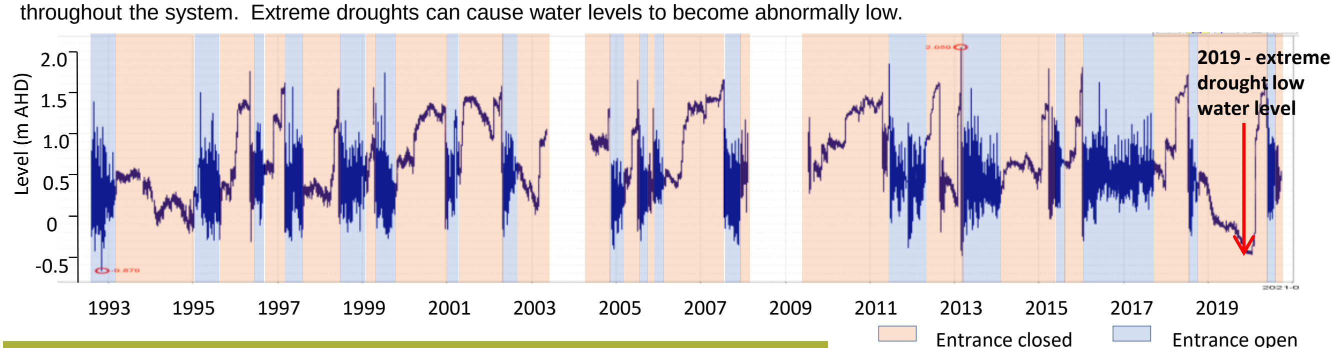
The artificial channel converted Lake Innes from a freshwater lake to a saline estuarine habitat – although it can be intermittently fresh after heavy rainfall. The salt caused shorelines to recede and brought about the dieback of fringing swamp forests and freshwater reed habitats. Evaporation during very dry periods causes extreme hypersaline conditions which negatively impacts estuarine habitat.

A foundation for more acid:

The introduction of marine sulfate to Lake Innes sediment with pre-existing high organic-matter contents, has enabled the formation of a *new layer* of sulfidic sediments across the lake bed. Importantly, these new sulfidic layers are near the surface of the lake bed, which means they are easily exposed to air when water levels drop i.e. when the entrance is breached or during an extended drought. Exposure to air causes pyrite and iron sulfides to oxidise and form sulfuric acid. This also can also lead to the release toxic trace metals.

Water levels: tides and droughts

The Lake Cathie system is an ICOLL. Entrance closure is the naturally dominant condition. Water level variations in the lake system are highly influenced by whether the entrance is open or closed. When open, semi-diurnal tides occur at the lower reach near the entrance, but are very small in Lake Innes (<5cm). In contrast, fortnightly tides and sea level anomalies cause up to 2.55m water level variation throughout the system. Extreme droughts can cause water levels to become abnormally low.

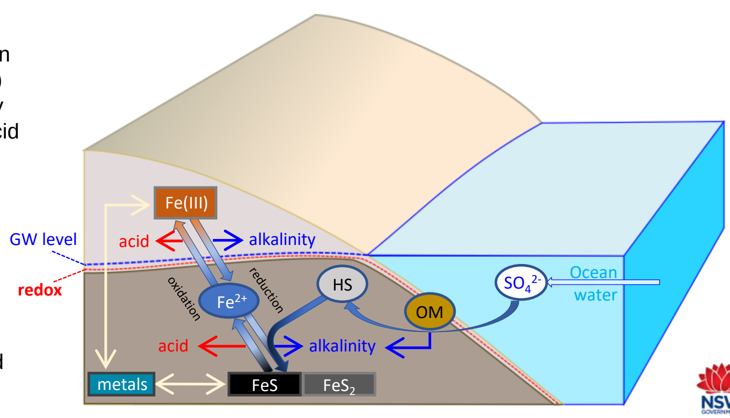


Acid sulfate soil processes – chemistry that reverses direction

Water levels control sediment chemistry - Groundwater levels influence the oxygen content of estuary sediments. Below the water table, low oxygen reducing conditions often prevail and iron sulfides can form. Above the water table oxic conditions occur and can oxidise iron sulfides. The red dashed 'redox' line in the graphic shows this boundary. Reactions that form or oxidise iron sulphides can *reverse direction* depending on water levels.

Oxidation pathways – when iron sulfides (FeS and FeS_2) are exposed to oxygen, they oxidise and make sulfuric acid and dissolved Fe^{2+}. Fe^{2+} oxidises further, thereby releasing more acid and forming solid iron oxides (Fe[III]). These processes create 'acid sulfate soils'

Heavy metals released from iron sulfides are often bound with Fe(III) compounds.



Reduction pathways - under reducing conditions, solid Fe(III) and sulfate (SO_4^{2-}) are converted by bacteria into soluble Fe^{2+} and hydrogen sulfide (HS). The HS reacts with Fe^{2+} to form solid iron sulfide compounds (FeS and FeS_2) which are stable ***if*** maintained in a reducing environment (under water). These processes generate alkalinity and consume acidity.

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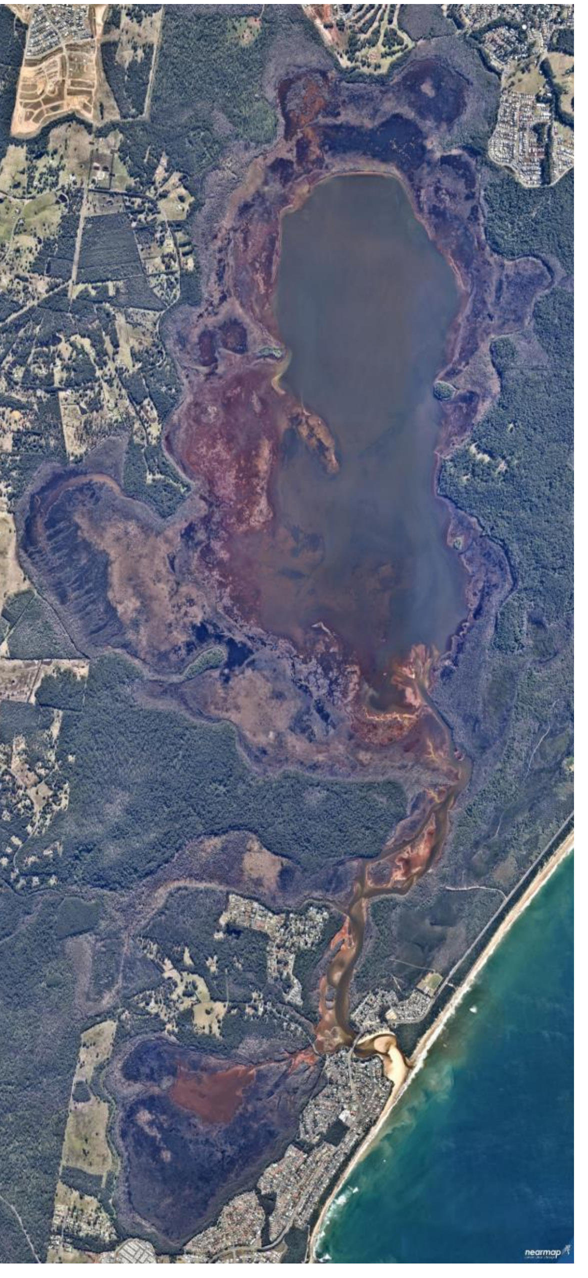
Future trajectories and management options

The combination of acute drought, re-flooding and partially reverted chemistry, followed by a fast draw down of water levels caused by the opening of Lake Cathie in May 2020, resulted in seepage of groundwater into the lake that was rich in Fe^{2+}. This Fe^{2+} quickly oxidised, forming solid Fe(III) and created an unprecedented mass iron-floc event in May 2020. This event highlights the impacts arising from cumulative long-term shifts in the system due to the artificial channel interacting with sediment chemistry, entrance opening and climate.

The image (right) taken soon after the event clearly shows the extent of iron-floc throughout the system. The large contribution of Lake Innes via the artificial channel is evident. This sequence of events will affect the lakes for decades. Without appropriate management, similar events are likely to occur in the future, especially given the predicted increase in climatic extremes with climate change.



Current situation

Sediment surveys by the Soil Conservation Service have confirmed widespread presence of sulfidic sediments and acid sulfate soil materials across the Lake Innes and Lake Cathie systems. The iron floc event of 2020 represents a mass translocation of iron, causing it to be transported out of the deeper sediments into surface water and onto surface sediments. This event will impede recovery of the system in the short term and will influence the geochemistry of the sediments in the long-term.

Business as usual

The imperative to manage flood risk in urban areas of Lake Cathie means there will likely be ongoing pressure to artificially open the entrance. Maintenance of the hydrological connection between the lakes combined with continued artificial opening of the entrance will likely lead to further iron floc events in the future. For example, the recent accumulation of iron floc on surface sediments may encourage further re-formation of new iron sulfides under wet / reflooded conditions, *but they will be close to the surface* where they are more prone to oxidation during drought.

Climate change is predicted to increase the frequency and duration of droughts, and the severity of extreme rainfall events along the NSW coast. There is a genuine risk that the processes described here will become increasingly cyclical and will continue to further degrade the habitat and amenity values of the system.

Management principles

Key principles to guide future potential management strategies include:

- Limit the exposure and oxidation of sulfidic sediments
- Promote *extended inundation* of sulfidic sediments to facilitate reduction pathways re-binding of iron as FeS_2 and generation of alkalinity
- Promote more stable lake water levels to a) keep FeS_2 under reducing conditions and b) prevent rapid lake draw down and creation of effluent groundwater gradients on the lake margins
- Promote the development of stable, high value wetland and aquatic habitats

Decouple Lake Innes from Lake Cathie

Ongoing artificial opening of the Lake Cathie entrance for flood mitigation presents a significant challenge to achieving the above principles. Fulfilling the principles requires the decoupling the Lake Innes system from the Lake Cathie ICOLL. This could be achieved by the placement of a sill or adjustable barrier in the artificial channel. Some issues, merits and risks associated with this strategy are listed below.

- Reinstating a barrier in the artificial channel would increase the mean water level in Lake Innes, decrease water level variation due to fortnightly tides, and retain a stable water level in Lake Innes in the event of an entrance breach.
- Rapid draw down of Lake Innes water levels and subsequent fast seepage of porewater, would be prevented.
- Water levels in Lake Innes would be controlled by the balance between freshwater inputs and evaporation, and would therefore be subject to large interannual oscillations due to drought/flood cycles linked to ENSO and IPO fluctuations.
- The impacts of droughts on water levels could be partially offset by retaining water in Lake Innes at a higher level. This is unlikely to increase flooding in private lands, however implication for vegetation communities would need to be assessed.
- Prolonged inundation of sulfidic sediments in Lake Innes will promote the formation of reduced iron sulfides and production of alkalinity, however these are still prone to re-oxidation during drought induced low water levels.
- Lake Innes would likely become a freshwater habitat, with a reduced import of marine alkalinity for buffering acidity, however sulfate reduction would continue due to residual sulfur within the system.
- Existing saltmarsh within Lake Innes would rapidly transition to freshwater wetland species due to existing seed stores
- Fire suppression in wetland vegetation during drought times is critical to maintaining system function and reducing ASS risk.

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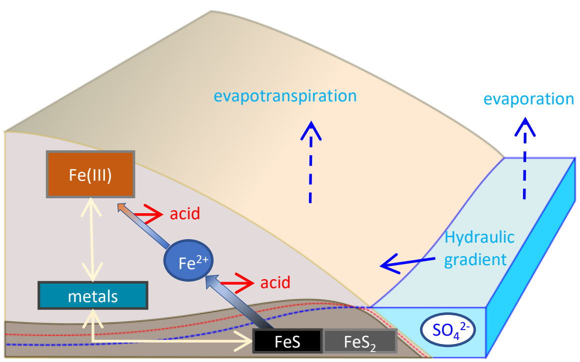
An artificial entrance breach made in July 2018 resulted in drainage of the lake to -0.1m AHD with the entrance closing rapidly. Subsequent drought conditions over the following year saw water levels in the lake drop further to historically low levels, thereby exposing up to 900 hectares of sulfidic sediments to oxidation.

Entrance closed – extended **drought 2019**

- Lake water level decreases to <0.5m AHD
- Low groundwater level on lake edge
- Large area of PASS sediments exposed to air in Lake Innes
- Formation of ASS. Oxidation of pyrite FeS_2, release of metals
- Large and unprecedented acid production
- Increased store of oxidised iron minerals, solid Fe(III)
- Metals associate with Fe(III)

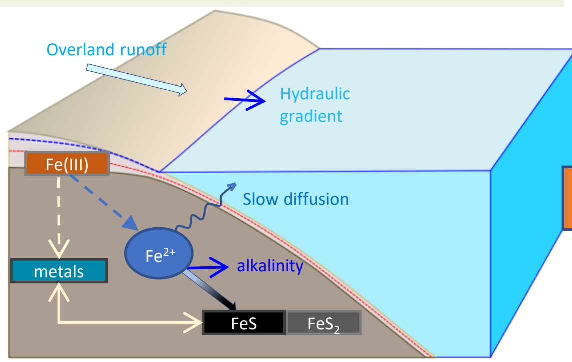


Lake fills

A series of rainfall events filled the lake in early 2020, prompting an artificial entrance opening on the 23rd May 2020 as water levels reached the local flooding threshold of 1.6m AHD.

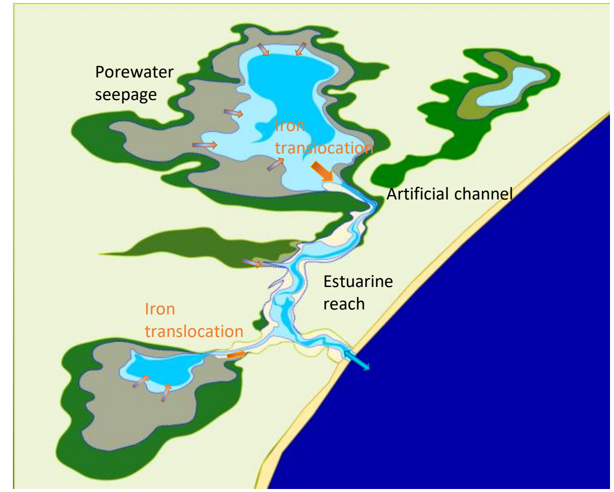
Closed entrance – **rainfall fills Lake**

- Water levels rise to 1.6m AHD
- Previously exposed areas inundated
- Sediments become reducing
- Solid Fe(III) reduced to soluble Fe^{2+}
- Groundwater on lake fringes becomes highly enriched in Fe^{2+}
- Some metals also dissolved
- **If allowed sufficient time**, Fe^{2+} eventually converts back to FeS_2 and lake returns to pre-drought state



Lake drains

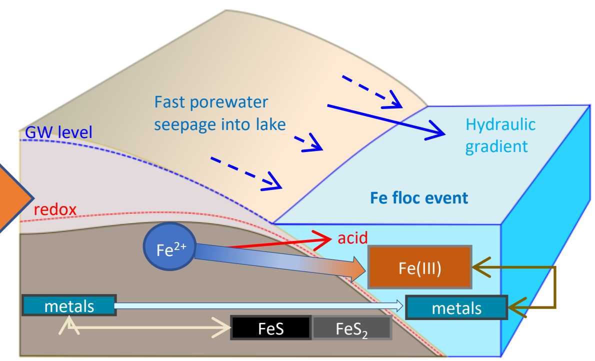
Drainage of the ICOLL system after the entrance breach caused a massive export of dissolved reduced iron (Fe^{2+}) from sulfidic sediment porewaters which rapidly oxidised to particulate iron oxides (orange-coloured 'iron floc'), smothering sediments throughout the system.



Entrance breakout / **ICOLL opening**

- **Rapid drop** in lake levels to mean tide level **before** Fe^{2+} has been converted back to FeS_2
- Large groundwater gradients develop towards lake
- Porewater rich in soluble Fe^{2+} and metals drains into lake
- Fe^{2+} exposed to air, oxidises, rapidly forms solid Fe(III) floc **in the lake** and generates acidity = **Mass iron floc event**
- Metals associate with newly formed Fe(III) floc

Iron floc event



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