# Probabilistic Analysis of Mine Void Salinity and Lake Level Associated with Climate Change

By
Rio Tinto Iron Ore
Eddy Lim (Specialist Hydrogeologist)
Kirsty Beckett (Specialist Hydrologist)
Wilhelm Jaen (Specialist Mining Engineer)
Atish Kumar (Principal Advisor – Mining)

- Predicting salinity levels in lake-forming mined out voids after mine closure has been a challenge since consideration of mine closure becomes part of open pit mine planning.
- What is certain is that the pre-mining environment will be changed.

- Understanding hydrologic and hydrogeologic cycles alone is complex and the impact of climate change on these cycles is difficult to predict using complex ocean-coupled climate models.
- A risk based approach using Monte Carlo simulation simplifies the mechanisms for assessing the uncertainties associated with the numerous potential hydrologic interactions used to estimate pit-lake salinity.

- The Monte Carlo approach overcomes the limitation posed by traditional sensitivity analysis, mostly vary one variable at a time, which becomes cumbersome if more than two values are allowed to change concurrently.
- The methodology also enables simple future or past climate scenarios to be used, such as increasing rainfall or evaporation rates, for comparison with existing climate outcomes to qualify climate change risk.

## The Site

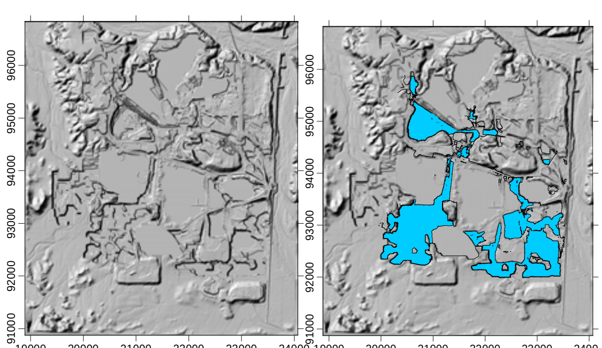

## Pilbara Hamersley Range

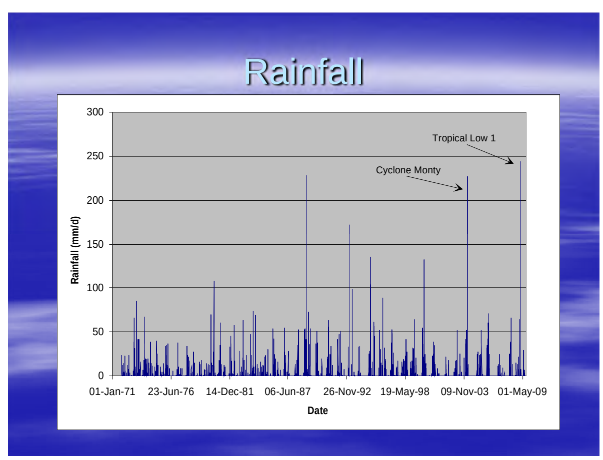
## Pilbara Aboriginal Art


## Pilbara Water Hole


## Gum trees

## A Mine in the Pilbara



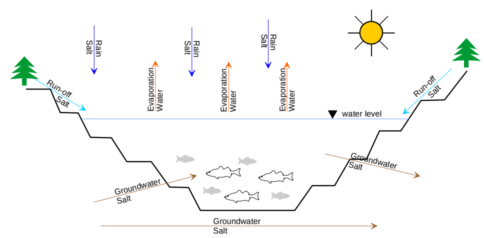



## Cyclone Monty – Mar 2004

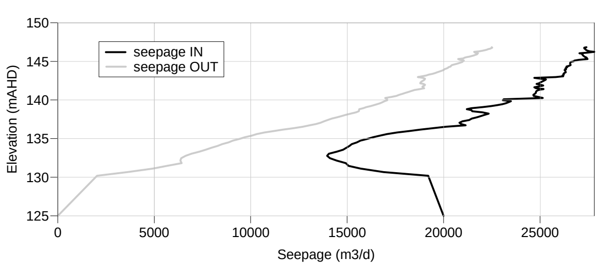

## Tropical Low 1 – Feb 2009


## February 2009

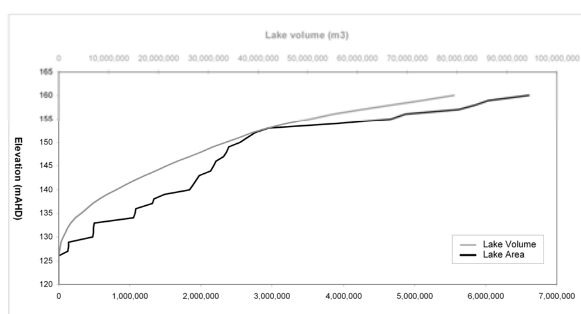

## Water and Salt Balance Model




## Pit-lake seepages from numerical model




## Pit-lake volume and area versus elevation



## Water Balance Calculation

Initial conditions

$h(0) = h_o$
$A(0) = A_o$
$V(0)=V_o$

**VOL(t) = VOL(t-1) – LSO(t-1) – OF(t) + IR(t) + CR(t) + GWI(t) – ELS(t)**

where

| | |
|---|---|
| h(t) = f[VOL(t)] | lake level |
| LSO(t) = g[h(t)] | lake seepage out |
| OF(t) = VOL(t) – LVOL | lake overflow<br>OF(t) = 0, if VOL(t) =< LVOL<br>LVOL = storage capacity of lake |
| IR(t) = F[h(t)] * R(t) | incidental rainfall |
| CR(t) = RC * [CA – F[h(t)]] | catchment runoff, RC = Runoff coefficient |
| GWI(t) = f[h(t)] | groundwater inflow |
| ELS(t) = F[h(t)] * E(t) | evaporation from lake surface |

## Salt Balance Calculation

Initial condition

$ML(0)=V_o$ * [Groundwater]

**ML(t) = ML(t-1) - MLSO(t-1) - MOF(t-1) + MR(t) + MGWI(t)**

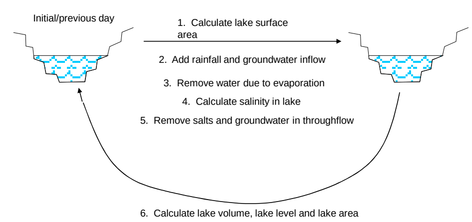
where

| | |
|---|---|
| MLSO(t) = LSO(t) * [ML(t) / VOL(t)] | Mass of salts in lake seepage out |
| MOF(t) = OF(t) * [ML(t) / VOL(t)] | Mass of salts in lake overflow |
| MR(t) = (IR(t) + CR(t)) *[Rain] | Mass of salts from rain<br>[Rain] = concentration of salts in rain |
| MGWI(t) = GWI(t) * [Groundwater] | Mass of salts in groundwater inflow<br>[Groundwater] = concentration of salts in groundwater |

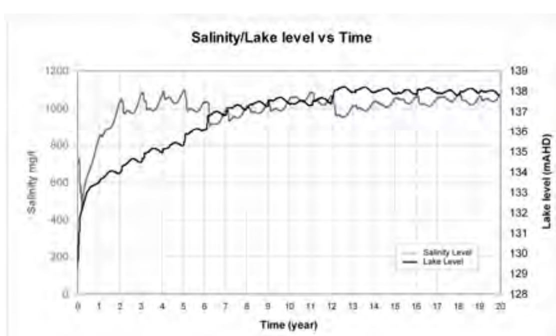
## Assumptions

- Complete and instantaneous mixing.
- No salinity stratification.
- No reduction in evaporation due to high salinity.
- No increase in evaporation close to the shore of the pit where the water is shallow.
- No increase in groundwater inflow from large rainfall events.

## Calculations




## Pit-lake salinity and level versus time




## Monte Carlo Simulation

- The term Monte Carlo method was coined in the 1940s by physicists working on nuclear weapon projects. It is named after the city in Monaco, where the primary attraction is casino that have games of chance. Gambling games, like roulette, dice, and slot machines, exhibit random behaviour.

## Rainfall Statistics

| Month | num | Min | Max | Stdev | Median | min | max | |
|---|---|---|---|---|---|---|---|---|
| January | 1 | 0 | 500 | 6.31 | 4.4 | 0.2 | 1.0 | |
| Feb | 2 | 0 | 500 | 10.30 | 5.1 | 0.3 | 1.0 | |
| Mar | 3 | 0 | 500 | 10.1 | 3.5 | 0.4 | 1.0 | |
| April | 4 | 0 | 500 | 4.45 | 2.1 | 0.3 | 1.0 | |
| May | 5 | 0 | 300 | 4.43 | 3.6 | 0.2 | 1.0 | |
| June | 6 | 0 | 500 | 5.06 | 3.6 | 0.2 | 1.0 | |
| July | 7 | 0 | 300 | 2.66 | 2.2 | 0.2 | 1.0 | |
| Aug | 8 | 0 | 300 | 1.51 | 2.4 | 0.1 | 1.0 | |
| Sep | 9 | 0 | 300 | 0.393 | 2 | 0.0 | 1.0 | |
| Oct | 10 | 0 | 300 | 0.682 | 1.9 | 0.0 | 1.0 | |
| Nov | 11 | 0 | 500 | 1.67 | 3.2 | 0.0 | 1.0 | |
| Dec | 12 | 0 | 500 | 3.4 | 3.8 | 0.1 | 1.0 | |
| Runoff coeff | | 50% | 200% | 25% | 0.4 | 40 | rainfall yielding runoff | |

## Rain Days Statistics

| | month | Min days | Max days | Mean | Stdev |
|---|---|---|---|---|---|
| January | 1 | 0 | 22 | 10.9 | 4.4 |
| Feb | 2 | 0 | 22 | 13.1 | 4.4 |
| Mar | 3 | 0 | 19.5 | 10.2 | 3.9 |
| April | 4 | 0 | 9.25 | 4.86 | 1.85 |
| May | 5 | 0 | 11.7 | 5.17 | 2.34 |
| June | 6 | 0 | 12.6 | 5.17 | 2.52 |
| July | 7 | 0 | 10.55 | 4.6 | 2.11 |
| Aug | 8 | 0 | 9.7 | 2.8 | 1.94 |
| Sep | 9 | 0 | 3.15 | 1.09 | 0.63 |
| Oct | 10 | 0 | 3.1 | 0.914 | 0.62 |
| Nov | 11 | 0 | 3.95 | 1.5 | 0.79 |
| Dec | 12 | 0 | 15.4 | 5.95 | 3.08 |

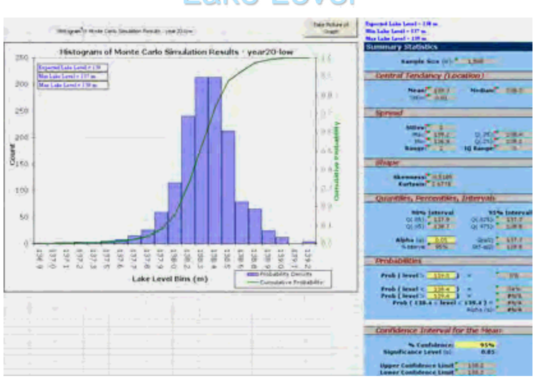
## Evaporation Statistics

| Month | num | Min Value | Max Value | Stdev | Mean |
|---|---|---|---|---|---|
| January | 1 | 2 | 13 | 14% | 7.9 |
| Feb | 2 | 2 | 13 | 10% | 7.2 |
| Mar | 3 | 2 | 13 | 14% | 7.2 |
| April | 4 | 2 | 13 | 9% | 6.4 |
| May | 5 | 2 | 13 | 8% | 5 |
| June | 6 | 2 | 13 | 6% | 4.3 |
| July | 7 | 2 | 13 | 6% | 4.3 |
| Aug | 8 | 2 | 13 | 7% | 5.1 |
| Sep | 9 | 2 | 13 | 6% | 6.4 |
| Ocy | 10 | 2 | 13 | 5% | 7.7 |
| Nov | 11 | 2 | 13 | 10% | 8.3 |
| Dec | 12 | 2 | 13 | 8% | 8.4 |

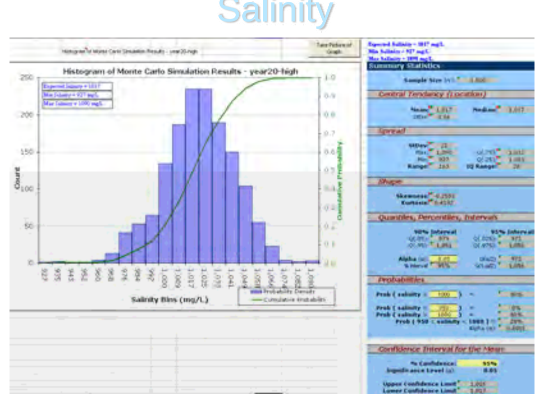
## Seepage

| | min | max | sigma | mean |
|---|---|---|---|---|
| gwinflow | -20% | 20% | 6.7% | 0 |
| gwoutflow | -20% | 20% | 6.7% | 0 |

## Lake Level




## Salinity



## Conclusions

- We are not committed to a single value.
- We are not committed to a range of values.
- We are committed to a range of probable values based on the uncertainties in the input variables.

## Acknowledgements

- The authors would like thank Rio Tinto Iron Ore for the support and opportunity to share this work at the 2010 IMWA conference in Sydney, Nova Scotia, Canada.

Thank you

## Conclusions

- Prediction of salinity and lake levels in pit-lake relies on assumptions and estimates on the input variables in the model. When there is significant uncertainty or natural climate variability associated with the inputs, traditional pit-lake numerical groundwater model approaches for assessing closure plans can be inadequate.
- The risk based Monte Carlo method enable a range of potential hydrologic and hydrogeologic conditions to be quickly modelled consistent with the level of confidence associated with each input.
- The resulting probability density and cumulative probability graphs represent all likely hydrologic and hydrogeologic condition, are simple to interpret and provide a transparent, risk based approach to closure as encouraged by Australian government regulators.

**WATER TABLE AT 138.5mRL**