The Flash-Flood Paradox in Semi-Arid Small Reservoirs:

Digital Twin Modelling of Hydro-Climatic Regime Boundaries for Climate-Resilient Agro-Ecosystems

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1. Why this matters

Small reservoirs support agricultural water security in semi-arid regions.
But their reliability is shaped by two interacting pressures:

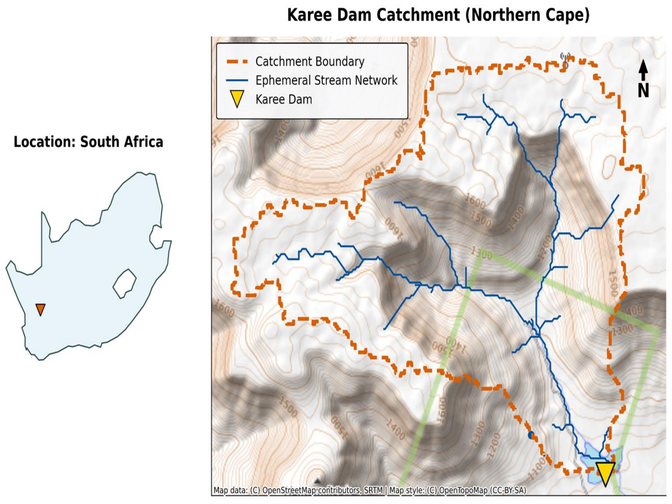
- Climate drying
- Catchment degradation

In degraded dryland catchments, less spillway overflow may not mean lower flood risk.
It may signal chronic reservoir depletion.

2. Study area

Karee Dam catchment, Northern Cape, South Africa

- Semi-arid agricultural landscape
- Catchment area: 16.91 km²
- Small reservoir system
- High rainfall variability
- Strong evaporative demand



3. Research question

Does catchment degradation always increase flood risk in small semi-arid reservoirs?

We tested whether degradation and climate stress can:

- Increase rapid runoff during storms
- Reduce long-term storage reliability
- Suppress spillway overflow under chronic water deficit

4. The Flash-Flood Paradox

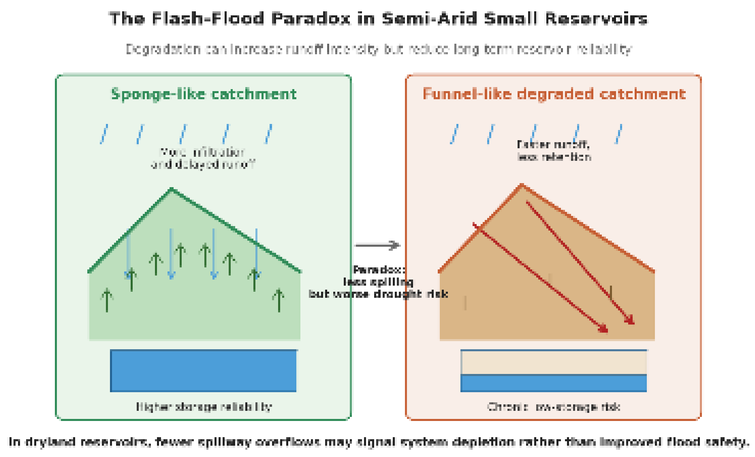
Vegetated catchment = Sponge

- More infiltration and slower runoff
- Higher landscape water retention

Degraded catchment = Funnel

- More bare soil and faster runoff response
- Lower infiltration and weaker buffering

Paradox:
A degraded catchment may generate flashier runoff, but the reservoir may spill less because long-term storage is depleted.



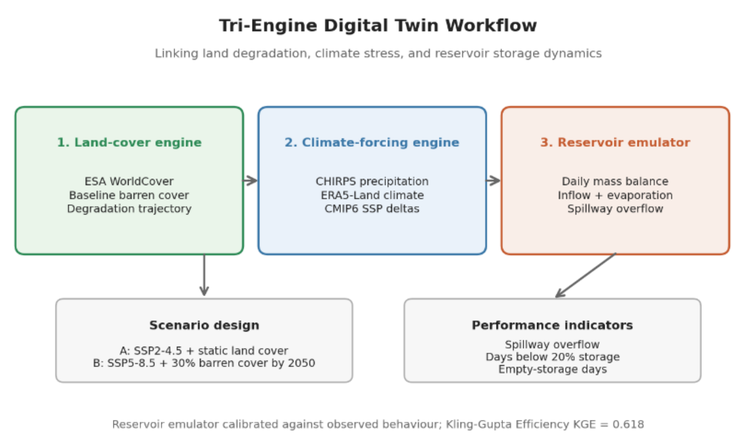
5. Digital twin workflow

A coupled land–climate–reservoir digital twin simulated daily reservoir behaviour from 2021 to 2050.

Three model engines:

- Land-cover engine: ESA WorldCover, baseline vs degraded states
- Climate-forcing engine: CHIRPS, ERA5-Land, CMIP6 deltas
- Reservoir emulator: Daily mass balance (KGE = 0.618)

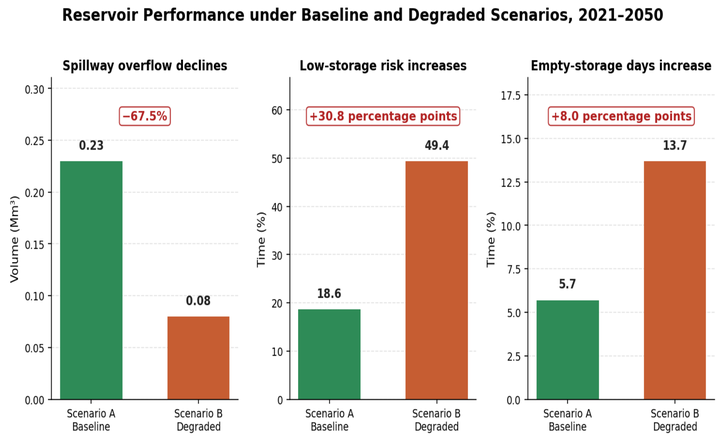
Scenario A (Baseline): SSP2-4.5, 2.58% barren cover
Scenario B (Degraded): SSP5-8.5, 30% barren cover by 2050



6. Key results (2021–2050)

Under the degraded high-stress pathway:

- Spillway overflow decreased by 67.5%
- Overflow volume declined from 0.23 to 0.08 Mm³
- Days below 20% storage increased from 18.6% to 49.4%
- Empty-storage days increased from 5.7% to 13.7%
- 23.5% of ensemble cases showed complete spill suppression



7. What the results mean

The degraded scenario produced fewer spillway events.
But this was not a success signal.

It reflected:

- Lower reservoir recovery
- More frequent low-storage conditions
- Higher probability of empty-storage days
- Reduced resilience under climate stress

Key interpretation:
Fewer floods can mean the reservoir is too depleted to spill.

8. Take-home message

Reduced spillway overflow is a warning signal, not a success story.

In semi-arid reservoir systems, flood indicators must be interpreted together with storage reliability.

Adaptation implication:
Climate-resilient reservoir planning should combine:

- Catchment restoration
- Demand management
- Climate-informed reservoir operation
- Monitoring of low-storage thresholds