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The flash-flood paradox: Digital twin modelling of hydro-climatic regime boundaries for climate-resilient agro-ecosystems in South Africa

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Abstract

Ephemeral catchments in arid and semi-arid regions underpin the water security of vulnerable agroecosystems. Adaptation planning in these regions is increasingly challenged by the simultaneous and potentially competing effects of land degradation and anthropogenic climate change. Conventional impact assessments often assume that increasing surface barrenness (e.g., vegetation loss and soil crusting) linearly amplifies runoff coefficients and flash flood magnitude. This study tests this assumption by introducing a reproducible Tri Engine Digital Twin to quantify the Flash Flood Paradox: conditions under which severe meteorological drought suppresses spillway-generating floods despite a progressively more runoff-prone landscape.

Applied to the Karee Dam catchment (16.91 km^2) in South Africa's Northern Cape, the framework couples (i) Earth-observation land-cover baseline mapping from ESA WorldCover, (ii) bias-corrected daily hydro-climatic forcing from CHIRPS and ERA5 Land extracted via Google Earth Engine, perturbed with CMIP6 monthly delta mapping from MPI ESM1 2 HR (SSP2 4.5 and SSP5 8.5), and (iii) a daily reservoir mass balance emulator optimised using Differential Evolution (monthly KGE = 0.618). Future analogue simulations for 2021–2050 show that under an extreme coupled pathway (SSP5 8.5 with a degradation trajectory toward a 30 % barren fraction by 2050), the cumulative 30 year spillway overflow declines from 0.23 to 0.08 Mm^3 (-67.5 %) relative to a moderate baseline (SSP2 4.5; static 2.58 % barrenness). In parallel, water supply reliability deteriorates sharply, with days below 20 % storage increasing from 18.6 % to 49.4 % and empty reservoir days rising from 5.7 % to 13.7 %. A two-dimensional regime map further identified a substantial drought-limited domain in which overflow was entirely suppressed, regardless of land conditions (132 of 561 stress-test cases).

These findings indicate that for extremely dryland agro-ecosystems, the dominant hazard can shift from episodic flood extremes to chronic water deficits, implying that flood-centric grey infrastructure may become maladapted without concurrent landscape rehabilitation and demand-side adaptation. The proposed digital twin workflow provides a transparent, transferable approach for mapping hydro-climatic regime boundaries to support climate-resilient planning.

Keywords: Climate resilience, CMIP6, dryland hydrology, ephemeral catchments, hydro-climatic regimes, land degradation, reservoir reliability

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