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The Flash-Flood Paradox: Catchment Degradation, Climate Stress and Reservoir Reliability in South African Agro-Ecosystems

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Abstract

Small reservoirs are essential in semi-arid agricultural landscapes, but their reliability depends on both climate and catchment conditions. This study investigates the “Flash-Flood Paradox” in the Karee Dam catchment, South Africa, where degradation may increase rapid runoff while reducing long-term storage reliability. A land–climate–reservoir workflow was applied for 2021–2050 using satellite land-cover, CHIRPS, ERA5-Land and CMIP6 data. Two futures were compared: Scenario A, a baseline SSP2-4.5 pathway with static land cover, and Scenario B, a degraded SSP5-8.5 pathway with barren cover increasing to 30% by 2050. Cumulative spillway overflow declined from 0.23 Mm³ in Scenario A to 0.08 Mm³ in Scenario B, a reduction of 67.5%. Days below 20% storage increased from 18.6% to 49.4%, while empty-storage days increased from 5.7% to 13.7%. A 561-case stress-test ensemble showed complete spill suppression in 23.5% of configurations. Reduced spillway activity should therefore not be interpreted as lower risk. In degraded semi-arid catchments, spill suppression may indicate chronic deficit. The findings support catchment restoration and integrated reservoir management for dryland water security.

Introduction

Small reservoirs support livestock, irrigation, domestic water use and drought buffering in semi-arid agricultural regions. However, reservoir reliability is not controlled by climate alone. Catchment conditions, particularly the balance between vegetated and bare surfaces, influences infiltration, runoff generation, soil-water storage and the timing of inflows.

Land degradation can produce an apparently contradictory hydrological response. Reduced vegetation cover, soil crusting and expansion of bare ground may increase runoff efficiency during intense rainfall events, causing degraded catchments to behave like hydrological “funnels”. Yet the same processes can reduce infiltration, root-zone storage and landscape moisture retention, weakening the catchment’s ability to sustain inflow during dry periods. Under climate stress, this can produce the Flash-Flood Paradox: fewer spillway overflows occur not because the system has become safer or more efficient, but because reservoir storage is increasingly depleted.

This distinction is important for agricultural water-security planning. Spillway overflow is often interpreted as evidence of excess water or flood potential. In small semi-arid reservoirs, however, reduced spillway activity may also indicate that inflows are no longer sufficient to overcome

evaporation losses and water demand. This paper evaluates the Flash-Flood Paradox using the Karee Dam catchment in South Africa’s Northern Cape Province. We assess how degradation and climate stress affect spillway overflow, low-storage conditions and empty-storage days during 2021–2050.

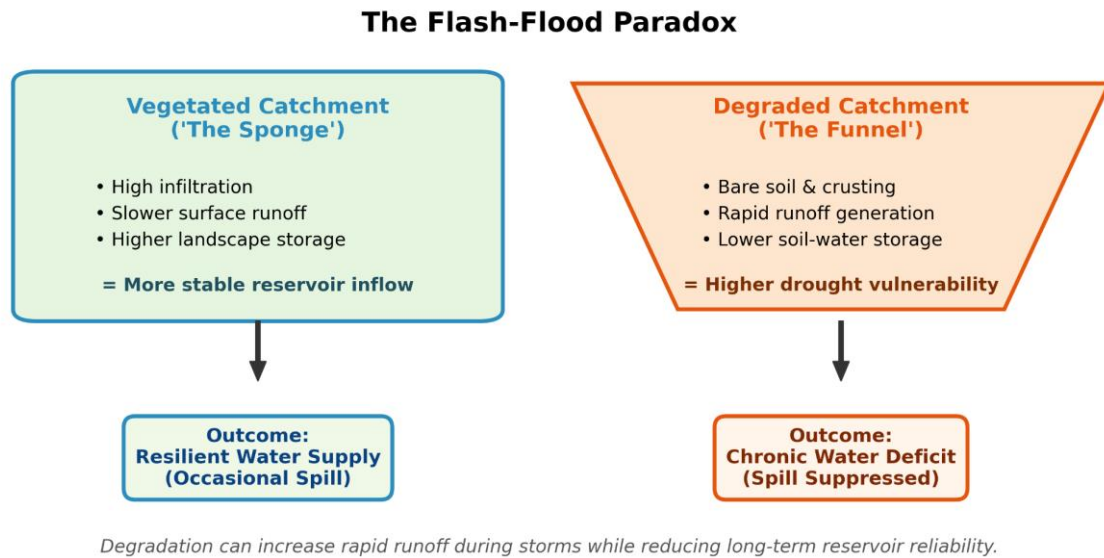


Figure 1. Conceptual representation of the Flash-Flood Paradox. Vegetated catchments act as hydrological “sponges”, supporting infiltration and gradual inflow, while degraded catchments act as “funnels”, promoting rapid runoff but weakening storage reliability under climate stress.

Material and Methods

The study focused on the 16.91 km² Karee Dam catchment in South Africa’s Northern Cape Province, a semi-arid small-reservoir system shaped by rainfall variability, high evaporative demand and land-cover condition. A land–climate–reservoir workflow simulated daily reservoir behaviour from 2021 to 2050.

The land-cover component used ESA WorldCover data to represent baseline catchment conditions, with particular attention to barren and sparsely vegetated surfaces (Zanaga et al., 2022). These data provided the basis for distinguishing between relatively vegetated “sponge-like” conditions and degraded “funnel-like” conditions. The climate component combined CHIRPS precipitation (Funk et al., 2015) and ERA5-Land climate variables (Muñoz-Sabater et al., 2021). Climate forcing was adjusted using available in-situ observations and perturbed using CMIP6 monthly climate deltas for SSP2-4.5 and SSP5-8.5, representing moderate and high climate-stress pathways (O’Neill et al., 2016; Eyring et al., 2016).

Reservoir behaviour was simulated with a calibrated daily mass-balance emulator accounting for inflow, evaporation losses, storage change and spillway overflow. Model performance was evaluated using the Kling–Gupta Efficiency, which integrates correlation, bias and variability components into a single hydrological performance metric (Gupta et al., 2009). The calibrated model achieved KGE = 0.618, indicating adequate skill for scenario-based reservoir assessment. Two contrasting scenarios were analysed. **Scenario A** represented a baseline SSP2-4.5 pathway with static or low-degradation land cover. **Scenario B** represented a degraded SSP5-8.5 pathway in which barren cover increased to 30% by 2050. Three reservoir-performance indicators were evaluated: cumulative spillway overflow, percentage of days below 20% storage, and percentage of empty-storage days. In addition, a 561-case hydro-climatic stress-test ensemble was used to identify the broader boundary between episodic spill-producing behaviour and chronic water-supply deficit.

Results and Discussion

The scenario comparison showed a strong shift in reservoir behaviour under the degraded high-stress pathway. Under Scenario A, cumulative spillway overflow reached 0.23 Mm³ during 2021–2050. Under Scenario B, cumulative spillway overflow declined to 0.08 Mm³, representing a 67.5% reduction. If interpreted alone, this decline could suggest reduced flood risk, but storage indicators show deteriorating reliability.

Days below 20% storage increased from 18.6% in Scenario A to 49.4% in Scenario B. This means that under the degraded high-stress pathway, the reservoir spent almost half of the simulation period in a low-storage condition. Empty-storage days also increased, from 5.7% to 13.7%. The reduction in spillway overflow was therefore not caused by more effective storage, but by a weakened reservoir water balance in which inflows were increasingly insufficient to offset evaporation losses and storage depletion.

Reservoir performance under baseline and degraded high-stress scenarios (2021–2050)

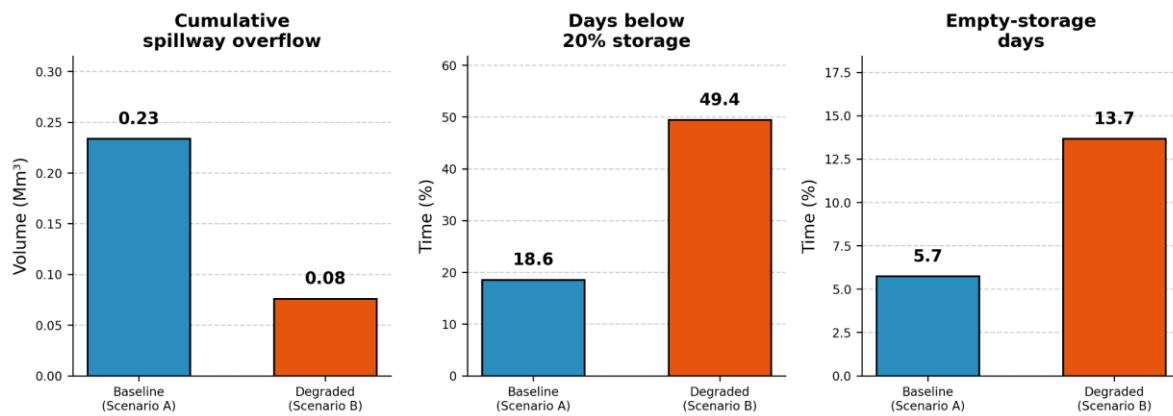


Figure 2. Reservoir performance under baseline and degraded scenarios, 2021–2050. Scenario B reduces spillway overflow but increases low-storage and empty-storage conditions, confirming the Flash-Flood Paradox.

The results demonstrate the central mechanism of the Flash-Flood Paradox. Degraded catchments can generate rapid runoff during individual storm events, but reduced infiltration and soil-water storage weaken the longer-term hydrological buffering function of the landscape. In semi-arid climates, where rainfall is episodic and evaporation is high, this loss of buffering can reduce the probability that reservoirs reach spill level. Thus, fewer spills do not necessarily indicate lower hydrological hazard or better water management. They may instead signal a transition toward chronic reservoir deficit.

The broader stress-test ensemble supports this interpretation. Of 561 hydro-climatic configurations, 132 cases, or 23.5%, resulted in complete spill suppression. This indicates that the transition from episodic spill-producing behaviour to persistent non-spilling behaviour is not limited to the two main scenarios. Rather, it represents a wider regime shift that can occur under specific combinations of reduced precipitation, increased evaporative demand, altered runoff response and catchment degradation.

For agricultural systems, this finding is important because reservoir failure often develops gradually before becoming visible as a crisis. Farmers and water managers may observe fewer overflow events and assume that water losses are declining, while the reservoir is actually moving toward a more fragile state. Conventional reservoir-focused interventions may therefore be insufficient if catchment processes continue to deteriorate. Raising dam walls or expanding storage capacity may provide limited benefits if inflow generation, infiltration dynamics and landscape water retention are degraded.

The findings highlight the need to treat catchment restoration as a water-security intervention. Revegetation, erosion control, soil-surface protection and reduction of bare ground can improve infiltration and landscape storage, supporting more stable reservoir inflows. These measures should be considered alongside reservoir operation, demand management and climate adaptation planning. In semi-arid agricultural systems, maintaining the hydrological function of the catchment may be as important as maintaining the reservoir infrastructure itself.

Conclusions and Outlook

This study assessed the Flash-Flood Paradox in a semi-arid small-reservoir catchment in South Africa. The results show that combined catchment degradation and climate stress can reduce cumulative spillway overflow while also worsening water-supply reliability. In the Karee Dam case, cumulative spill declined from 0.23 Mm³ under the baseline scenario to 0.08 Mm³ under the degraded high-stress scenario. Over the same period, days below 20% storage increased from 18.6% to 49.4%, and empty-storage days increased from 5.7% to 13.7%.

These findings show that spillway suppression should not automatically be interpreted as a positive outcome. In degraded semi-arid catchments, reduced spill may signal a shift from episodic flood production toward chronic reservoir deficit. For agricultural water security, the key implication is that catchment conditions must be managed as part of reservoir reliability.

Vegetation protection, soil restoration and degradation control are therefore not only environmental measures, but also practical water-security interventions.

Future work should extend the analysis to additional semi-arid reservoir systems and include socio-economic water-demand scenarios. Coupling reservoir simulations with farm-level water-use data, livestock requirements and adaptation-cost assessments would strengthen the policy relevance of the approach. The results presented here show that climate adaptation for small reservoirs must move beyond dam infrastructure alone and include hydrological restoration of the surrounding catchment.

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