Geophysical Research Abstracts
Vol. 21, EGU2019-11338, 2019
EGU General Assembly 2019


# Flip the bucket: why models based on deficits, not buckets, might be key to runoff projections in a drying climate

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Rainfall runoff models based on conceptual "buckets" are frequently used in climate change impact studies to provide runoff projections. Here we present an alternative deficit-based "flipped" bucket model and analyse the results when applied to a number of catchments in south eastern Australia.

In conceptual bucket models, a full bucket means a catchment is wet, while drainage or evapotranspiration cause the bucket storage to decline. However, since a bucket can be empty (zero storage), such models have a "driest possible state" that may not be reached in reality. When a model approaches this empty state, evapotranspiration approaches zero, which means the model may cease to track the moisture deficit accumulated during continuing dry conditions. In turn, the incorrect moisture deficit may cause overestimation of runoff from subsequent rainfall events, leading to long-term model bias if dry conditions persist for multiple years.

In contrast, deficit-based models are flipped buckets: the wettest possible state is zero deficit, so there is no a priori "driest possible state": the deficit can keep accruing as dry conditions continue. In this work we hypothesise that such models are inherently more capable of providing runoff projections under future drier conditions because they avoid the problems mentioned above.

To test this hypothesis, we take a commonly used conceptual bucket model, GR4J, and "flip" the main model storage to create a deficit-based model. Arbitrarily high deficits are avoided via a negative feedback mechanism: the more moisture is removed, the harder it is to remove more, but there is no limit on moisture removal. We apply both versions of the model to 38 temperate catchments in south-eastern Australia. The models are tested to see whether parameter sets exist that have good performance simultaneously on both wetter and drier multi-year periods, including the 13-year "Millennium" drought. Furthermore, the simulations are qualitatively compared to patterns in observed state variables such as groundwater and GRACE water storage.

The results from this analysis are clear: the alterations cause a marked increase in model performance and robustness, particularly in catchments where the storage in the original bucket model approaches empty every summer (typically the drier and flatter catchments). Thus, the tracking of deficits during dry periods is aided by removal of the inherent "driest possible state" in bucket models. However, the limitations of the approach are seen through comparisons with state variables: the simulated catchment wetness does not replicate the observed long-term downward trends, even with the model changes in effect. A way forward to resolve these issues is discussed. The results support a future research focus on deficit models (of which many exist beyond that presented here) to improve plausibility of future climate projections, particularly for regions subject to projected drying.