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A stakeholder driven, holistic water resources model for Malawi: applying the CWatM hydrological model.

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Groundwater is a key water resource. In Malawi it provides 82% of domestic, agricultural, and industrial water needs. However, despite its central importance to meeting social and economic targets, with over 14 million people reliant on groundwater to meet their everyday needs, the 'unseen' nature of groundwater makes management a challenge. Furthermore, minimal groundwater monitoring and measurement limit understanding of Malawi's of water security. To guide water management policy and practice, comprehensive modelling of Malawi's water resources, accounting for groundwater, is necessary. Here, to the best of our knowledge, we present the first process-based model of groundwater storage for the Lake Malawi Shire River Basin,which covers 94% of Malawi's surface area, confirming prior estimates of groundwater storage.

We apply a global hydrological model, the Community Water Model (CWatM), to Malawi. To effectively represent Malawi's water resources, we couple a high-resolution CwatM (5 arc minute resolution) with MODFLOW (5km resolution), enabling a high-resolution, national surface and groundwater model. Semi-structured stakeholder interviews were conducted to accurately represent Malawi's water governance, identifying key adjustments that reflect national water resources. Model modifications were implemented based on stakeholder engagement. Notably, we implement model modification to account for small-holder agriculture and 'dambo' wetlands. National characteristics of water and sanitation were also included; the model was developed to include pit-latrine sanitation, used by over 90% of the population. Spatial variation domestic water use, both source and quantity, between urban and rural areas was also incorporated. Such model modifications significantly improved model performance, we suggest similar developments should be considered in modelling national water resources in other southern-African countries.

Basin-wide scale model validation was undertaken by comparison with remote sensing observations of evapotranspiration, precipitation, and changes in total water storage (using GRACE Satellite data). Model calibration was undertaken by comparison to Global Data Runoff Centre

(GRDC) discharge data.

We model that 660km³ of available groundwater is stored within aquifer units in Malawi (the currently available estimate of groundwater storage in Malawi is between 96.7 and 1,108 km³). Our model shows a consistent decline in groundwater levels since 1960 (the beginning of our study period). In total, we estimate a decline of 11.6km³ in groundwater storage in Malawi since 1960, raising significant concerns for future water security in the country. Not only does this model provide unprecedented insight into Malawi's water security, particularly regarding the unseen but critical groundwater resource, further model development will enable forecasting of future water security issues under climate and socio-economic change.