Lake Malawi's threshold behaviour: A stakeholder-informed model to simulate sensitivity to climate change

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Abstract:

Over 90% of Malawi's electricity generation and irrigation depend on Lake Malawi outflows into the Shire River. Recent lake level declines have raised concerns over future climate change impacts, including the risk of no outflows if the Lake Malawi Outflow Threshold (LMOT) is passed. Addressing calls for model co-production, we iteratively engage stakeholders in data collection, and eliciting local system insights and management priorities, to inform the development of a Water Evaluation And Planning (WEAP) model for the Lake Malawi Shire River Basin. We use a simple model setup and manual calibration to allow for data sparsity and limited documentation of historical management decisions. The model satisfactorily captures limited observed streamflow patterns of Lake Malawi tributaries and lake level variations for the period 1960-2009, however, small errors in lake level simulation significantly affect simulation of monthly outflows. The riparian countries, Malawi, Tanzania and Mozambique contribute approximately 55%, 41% and 4% respectively to lake inflows (1960-2009 average). Forced with 29 bias-corrected global climate model projections (2021-2050) and assuming no change in current operating rules of key infrastructure, the WEAP model simulates wide-ranging changes. These include much higher lake levels that would cause downstream floods, and much lower lake levels, including 11 projections that fall below the LMOT. Both outcomes would have major implications for downstream hydropower and irrigation. Future water management plans require identification and evaluation of strategies that can address multi-year shifts in lake levels and the uncertainty inherent in future climate and hydrological model outputs.

Keywords: Lake Malawi; Shire River; Water Evaluation And Planning (WEAP); stakeholder engagement; climate change impacts

1. Introduction

Malawi's socio-economic development plans are reliant on the outflows from Lake Malawi into the Shire River. Hydropower expansion, increase in irrigated area, and greater provision of domestic water supply are central to national development plans. Installed hydropower capacity in Malawi is ~0.35 GW, which comprises ~94% of present electricity generating capacity, and plans include expansion to 1.0 GW by 2030 (Conway et al. 2018). Irrigation expansion is planned through both small distributed irrigation schemes and large scale projects like the Shire Valley Transformation Project and Green Belt Initiative. However, lake levels and outflows exhibit substantial variability over inter-annual, decadal and multi-decadal scales, which poses risks to water, food and energy security. For example, during a dry period in the early 20th century, Lake Malawi levels were lower than the Lake Malawi Outflow Threshold (LMOT) which resulted in no outflows from 1910-1924 (Nash et al. 2018). This effectively closed the Lake Malawi basin, with impacts on navigation and a reversal in the flow direction of the upper Shire River (Dixey 1924; Lyons et al. 2011; Birkhead et al. 2017). The recent 2015/16 drought was one of the most severe on record and it is estimated that anthropogenic warming has approximately doubled the risk of such a drought event occurring (Kolusu et al. 2019). Since 2015 a multi-year dry period (including the 2015/16 El Niño event) has led to prolonged low lake levels and reduced outflows, causing socio-economic disruption through impacts on hydropower generation leading to frequent load-shedding across the country (Conway et al., 2017). In contrast, during early 2015 large parts of the lower Shire River catchment experienced extreme flooding partly associated with high lake outflows but more directly due to heavy rainfall over the downstream catchment area (Rapolaki and Reason 2018). Floods in 2018 and 2019, including those caused by Cyclone Idai, also led to extreme flooding in the downstream reaches of the Shire River.

Future climate change could significantly alter regional rainfall patterns (McSweeney et al. 2010 a, b; Mittal et al. 2017; Warnatzsch and Reay 2019) which would affect Lake Malawi levels, with implications for the future performance of hydropower and irrigation infrastructure. Sustainability of Malawi's socio-economic development under climate change requires, understanding the potential changes, assessing their risks, and identifying management strategies to manage the dynamics between water resources availability and demand.

Previous hydrological studies in the Lake Malawi Shire River Basin (LMSRB) have simply taken a water balance approach (e.g. Kidd 1983; Neuland 1984; Shela 2000; Calder et al. 1995; Kumambala and Ervine 2010; Lyons et al. 2011) to assess how lake levels are sensitive to rainfall and land use change. These studies suggest that uncertainties, especially in observed rainfall and evaporation over the lake, critically affect the water balance. However, these studies have not addressed the significant influence of lake level regulation on outflows and downstream needs (hydropower plants, irrigation and wetland systems) and have focused more on understanding historical behaviour rather than potential future changes under climate change and/or change in water management decisions. Notably, they have not evaluated the implications of outflow regulation by the Kamuzu Barrage for downstream infrastructure, something that has become increasingly critical in recent decades as installed hydropower capacity and electricity demand have grown.

Recent water resources research has suggested that co-production approaches (also referred to as collaborative modelling, participatory modelling or stakeholder participation) can improve modelling tools, and increase their salience and credibility for stakeholders (e.g. Banhart et al. 2018; Ulibarri 2018). Model co-production incorporates stakeholder concerns, priorities, and input, to inform development and parameterisation of quantitative models, and actively incorporates their perspectives to make a model more fit-for-purpose (Eker et al. 2018). Incorporating stakeholder concerns helps customise both modelling and analysis, which is crucial for generating useful and usable information for stakeholders (Ulibarri 2018). In complex social and environmental systems that are undergoing rapid changes, such approaches are particularly important (Clark et al. 2016). Iterative multi-stakeholder engagement in water resources research helps generate knowledge about the management/decision context, because complementary competencies and experiences of researchers and stakeholders can be integrated into modelling (Bhave et al. 2018). Stakeholders often complement researchers' understanding of a system, provide underutilised information and observations, ensure relevance of alternative management options, and enable feasibility assessment of scenarios which help characterise uncertainties (Barnhart et al. 2018). The nature of collaborative approaches in model development affect how stakeholders view the credibility, salience and legitimacy of models, and the extent to which they might be used for decision making (Ulibarri 2018). In this study we seek to address two main research questions:

- To what extent is it possible to develop a water resource simulation model using stakeholder consultation for the Lake Malawi Shire River Basin system that incorporates historical water management decisions and captures observed variability?
- What are the potential impacts of climate change, as simulated by a wide range of climate model projections, on Lake Malawi levels, including the risk of lake levels falling below the Lake Malawi Outflow Threshold (LMOT)?

2. Methods

2.1. Study area characteristics

The LMSRB system is located in the southern part of the Great East Africa Rift Valley system (Delvaux 1995), and the Rift Valley has a significant influence on the shape and morphology of the entire region (Owen et al. 1990). The LMSRB is transboundary, covers an area of ~161,381 km^2 ,and is the most downstream major tributary of the Zambezi River (Figure 1). Lake Malawi is the third largest lake in Africa (about 28,999 km^2) and the fourth largest in terms of volume (roughly 7720 km^3) (Lyons et al. 2011). It has a catchment area (including the lake) of ~129,079 km^2; ~21% of the catchment lying within Tanzania, ~10% in Mozambique and the rest in Malawi. The rift faulting results in a relatively small land catchment area compared to the lake area (23% of total catchment). The catchments are characterised by steep upper slopes with mixed use subsistence and commercial farming. The Shire River is approximately 410km long and can be divided into three sections, the Upper, Middle and Lower Shire. The Upper and Lower are relatively flat and susceptible to expansion of the river causing flooding in low lying areas (Figure 2). The Middle Shire is steep and rocky and has an elevation drop of 370m over an 80km course. The hydropower potential in the Middle Shire has been tapped by the development of three stations (Nkula, Tedzani and Kapichira), with a combined installed capacity of nearly 346.3 MW (*c*. 94% of Malawi's electricity generating capacity) with infrastructure upgrades currently underway to add another 36MW at Nkula.

2.2. Hydrology and water balance of Lake Malawi

Lake Malawi covers an area of ~28,999 km^2, is 590 km long, 80 km wide at the widest point, has a maximum depth of 785 m, a mean depth of 292 m, and being a steep-sided lake requires a significant drop in lake level to affect lake surface area (Bootsma and Hecky 1993). Lake levels reach annual maxima at the end of the rainy season (March to May) when catchment rainfall and rainfall over the lake exceed lake evaporation, terrestrial evapotranspiration losses, and outflows to the Shire River. The minima is reached at the end of the dry season when inputs are lower than outputs. Key lake water balance components include, lake rainfall and evaporation, inflow from catchments, outflow to the Shire River, and groundwater interactions. Over inter-annual to decadal timescales geological/tectonic activity and sedimentation are less important factors affecting lake levels (Neuland 1984). Historical land use change (primarily conversion of forest cover to agriculture) has been extensive in recent decades and is likely to have changed the runoff coefficients and reduced residence time in Lake Malawi catchments (Neuland 1984); something indicated by model-based simulations (Calder et al. 1995; Palamuleni et al. 2011). Variability in lake evaporation is low in the historical period, and given the difficulty of obtaining accurate measurements, has generally been considered as a constant in the lake water balance (Neuland 1984). Outflows to the Shire River affect the lake water balance significantly as do changes in release policy at the barrage which regulates outflows, and these need to be factored into the water balance, as far as possible. Lake Malawi level changes over historical time scales have been studied extensively (e.g. Lyons et al. 2011). There have been three key eras in the evolution of this lake-basin system (Figure 3); pre-1965 era of natural flows before the construction of the Kamuzu Barrage, 1965-1993 era when the Kamuzu Barrage was operated using an elevation-outflow curve, and post 1993 era when Kamuzu Barrage releases were restricted.

Pre 1965: Oral history and archival documents indicate Lake Malawi levels were significantly lower in the pre-1850 era than the LMOT (~471.5 masl) (Owen et al. 1990; Nash et al. 2018). Paleo-climatological evidence suggests that significant lake level fluctuations have occurred in the past, and similarities with changes in Lake Tanganyika levels indicates that climatic changes may have played an important role (Owen et al. 1990; Delvaux 1995). Modern observations dating back to 1895 (Figure 3 shows levels from 1921) show that the LMOT was crossed in the early 20th century when lake levels dropped to ~470 masl. This stopped the outflow into the Shire River, effectively closing the Lake Malawi basin (Lyons et al. 2011). Dixey (1924) describes the impacts on navigation, silt deposition in the upper Shire River and river bed drying. Lack of outflows and silting of the upper Shire also led to the shrinking of Lake Malombe and increase in the height of two sandbars, one upstream and one downstream of Lake Malombe (Birkhead et al. 2017). Dixey (1924) reports how a stretch of ~60 kms of the upper Shire River reversed its flow direction; flowing north into Lake Malawi, instead of south towards the Zambezi.

1965-1993: The Kamuzu barrage at Liwonde was built in 1965 to manage lake variability and provide more sustained flows for downstream requirements; particularly hydropower. Similar to Lake Victoria, initially the outflows were regulated according to an agreed curve (Harrison et al. 1976; Kidd 1983; Kumambala 2010). In this period seasonal fluctuations were relatively stationary (Jury 2014). Lake Malawi water level fluctuations were influenced by a combination of climatic conditions and barrage operation decisions. Lake levels reached a historic high in 1979-80 (~477 m) when lakeshore areas experienced significant flooding. This prompted research into how or under what conditions such high levels might be reached again, and options for managing such conditions (Drayton 1984; Neuland 1984).

1994 onwards: After a prolonged drought during 1992 to 1995, lake levels fell (Jury 2014) and so from 1993 onwards the barrage restricted outflows to ~200 cumecs to raise lake levels. Outflow regulation by the Kamuzu Barrage effectively made Lake Malawi function like a reservoir. However, global databases like AQUASTAT (2011) or GRanD (2011) do not recognize it as such. If considered a reservoir it would be the third largest reservoir globally in terms of area. The volume of water in the lake above the LMOT that can be regulated by the barrage is about 100 km^3 (Lyons et al. 2011). Since the barrage upgrade under the Shire

River Basin Management Programme in 2018, the barrage has acquired the ability to raise lake levels to 477 masl, and now has a more sophisticated gate management system.

2.3. Climatology

The LMSRB has a mild tropical climate with an austral summer rainy season with rainfall predominantly from November to April. Regional climatology is complex because the area experiences influences of the East African Monsoon and the Southern African climatic regimes. Broadly, Lake Malawi catchments located in Tanzania are influenced more by the East African Monsoon and receive high rainfall (Yang et al. 2015), with multi-decadal variability associated with Indian Ocean Sea Surface Temperatures (Tierney et al. 2013). Annual rainfall in Malawi ranges from 800 to 1600mm per annum (Nicholson 2014), whilst Lake Malawi catchments in Tanzania receive around 1000 – 1600mm per annum (Yang et al. 2015). Low elevation, and high annual maximum temperature (~38°C) in the lower Shire river basin lead to higher evapotranspiration, while pockets of high rainfall, primarily due to topographic influences, are located along the western shores of the lake and around Mount Mulanje in southern Malawi (McSweeney et al. 2010 a, b).

2.4. LMSRB WEAP model

The Water Evaluation And Planning (WEAP) model (Yates et al. 2005 a, b) is used to assess climate change impacts and the effects of stakeholder-elicited adaptation options and pathways, among other applications. It has been extensively applied in Africa to assess the water and energy sectors, and the impacts of climate change (e.g. Droogers et al. 2012; Cervigni et al. 2015; Spalding-Fecher et al. 2017; Reinhardt et al. 2018). Globally, several studies have considered the sensitivity of river basins and water supply systems to climate change (e.g. Bhave et al. 2014; Safavi et al. 2015; Bhave et al. 2016; Ortiz-Partida et al. 2016). Some studies using WEAP have also assessed lake inflows, management and water allocation (e.g. Mehta et al. 2013; Karlberg et al. 2015) indicating that it is useful across a range of climatic, hydrological and socio-economic conditions.

Guided by previous research (e.g. Kumambala 2010, and Jury 2014) we developed a conceptual model of the LMSRB that included: the main rivers and tributaries; existing and proposed hydropower schemes; existing and proposed irrigation and domestic water supply dams and offtakes; and other important features including areas of intensive subsistence agriculture, national parks and wetlands and key infrastructure such as the Kamuzu Barrage. This provided a starting point for discussion with stakeholders in Malawi in June 2017 including staff from the Departments of Irrigation, Surface Water, and Agriculture Extension Services within the Ministry of Agriculture, Irrigation and Water Development (MoAIWD), the Department of National Parks and Wildlife, representatives of the Electricity Supply Corporation of Malawi Ltd, the Shire River Basin Management Programme, and operators of the Kamuzu Barrage. Stakeholders helped to build understanding of historical and current water resources management practices, shared documents and reports, identified and prioritised the catchments to be delineated for the model, and helped to characterise existing and planned infrastructural components. Consultations provided stakeholders with opportunities to highlight features and development priorities that were important to them and added missing elements to help develop a WEAP model structure that represented LMSRB hydrology and their requirements (Supplementary Information Figure 1).

2.5. Rainfall-runoff modelling and Lake Malawi formulation

We used climatological and hydrological data for the period 1960-2009, for 35 LMSRB catchments, compiled through the Second National Water Development Project (NWDP II); a study carried out by the MoAIWD in 2011. This data were compiled from 402 rain gauge stations (See Supplementary Information Figure 2 and Supplementary Information Table 1) to synthesise a continuous 50 year dataset following a detailed quality check by the MoAIWD. This involved collecting data from 867 rain gauges, and filtering the data to identify the most reliable series and minimise the amount of data infilling. The MoAIWD used three criteria for station selection; at least 20 years of data, at least 50% of complete data, and gauges with complete metadata (e.g. grid references), and identified 402 stations. Double mass analysis and least squares regression analysis were used for infilling and Thiessen polygon method used to generate area average rainfall for the lake basin catchments across all three countries. We use this quality-controlled, government-recognised rainfall dataset for the period 1960 – 2009 (National Water Development Project 2011). We also compared these observation-based data with the CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data) dataset (which combines observations and satellite data, Funk et al. 2015) to extend the period with available observations. However, as CHIRPS considerably overestimates rainfall (positive bias) compared to observations (Supplementary Information Figure 3), we did not extend the analysis period beyond 2009.

Reference evapotranspiration (ET_0) estimates from Food and Agriculture Organization (FAO), available through CLIMWAT (FAO, 2010) using Penman-Monteith, have been used in this study as explained in the database. Reference ET data from CLIMWAT is the most appropriate method to use for this study since the FAO undertook vigorous quality assurance in producing the data (National Water Development Project 2011). The potential evapotranspiration rates derived from CLIMWAT are long-term (1971 – 2000). Mandeville and Batchelor (1990) calculated the coefficient of variation of Penman evaporation to be 3% of annual average estimates from climate stations within Malawi (National Water Development Project 2011).

A bucket approach (mass balance) is used to simulate the lake hydrology, with catchment runoff and direct rainfall as inputs and evaporation and outflow to the Shire River as outputs (Figure 4). WEAP incorporates five method choices for representing catchment processes; including evapotranspiration, runoff, infiltration and irrigation demands. The choice of method depends on the decision context, stakeholders' requirements, level of complexity appropriate, and data availability. The simplest Rainfall-Runoff option is used here for the Lake Malawi catchments because the modelling objective is to simulate monthly lake levels in a region with limited data, and for developing a model that has low computational requirements to enable extensive scenario analysis. The model does not include groundwater recharge by the lake or groundwater-surface water interactions in the catchments. Net evaporation is input as a residual between ET_0 and rainfall, and can be positive or negative. Outflows to the Shire are a function of the reservoir operation as there are no forced abstraction/minimum flows prescribed. The "bucket" has straight sides, so the surface of the lake does not change with increase in surface elevation and storage. This modelling assumption is a limitation because changes in surface elevation can change the surface area affecting lake evaporation (a detailed lake area/level relationship was not available). Some other modelling-specific assumptions are presented in Table 1.

Manual calibration is carried out targeting streamflow in Lake Malawi catchments, and included testing a range of parameter values in an iterative approach. We use the two parameters in the WEAP Rainfall-Runoff method; crop coefficient (Kc) and effective precipitation, and lake outflow from the Kamuzu barrage operation for this approach. We considered that in an area of extreme data sparsity a simple rainfall-runoff model is acceptable as limited data availability preclude more sophisticated parameterisations. Initially, crop coefficient values that capture seasonal agriculture practices are developed based on the range of values provided by Allen et al. (1998) for land cover and cropping patterns specified in the NWDP II (National Water Development Project 2011) to simulate catchment streamflow observations. Lake catchment streamflow observations are discontinuous with many inconsistencies and insufficient for rigorous calibration. Therefore our focus is to obtain an acceptable estimate of total annual inflow to the lake, given our overall objective to simulate observed Lake Malawi levels. Using an appropriate Kamuzu barrage operation rule is important to achieve lake level and downstream flow simulation. However, the operation rule that determines the maximum hydraulic outflow has changed over time and therefore we do not apply a conventional split-series calibration-validation approach. We calibrate the Kamuzu barrage releases in two stages, first using operating rules (described by Harrison et al. 1976; Kidd 1983 and Kumambala 2010) for the period 1960-1993, and second using observed discharge at the Kamuzu barrage for the period 1994-2009 to constrain the maximum hydraulic outflow (Figure 3).

This approach aims to capture in a model of Lake Malawi for the first time the effects of historical decisions on barrage management on the lake water balance. This improvement also allows the model to be used to assess the effects of future barrage operation decisions and their impacts on Lake Malawi levels. Model performance is assessed over the full period (1960-2009). After formulating the conceptual model structure with stakeholders in June 2017, we discussed the model set-up again in November 2017, to incorporate comments about fine-tuning the model calibration. Stakeholders explained reasons why certain decisions regarding lake outflow regulation were made in the past, and how changing barrage operation rules were put in place to operationalise these decisions at different times – these insights were crucial to the model setup.

2.6. Future climate projections

Climate observations used for WEAP model setup are for the period 1960-2009, while the future climate projections represent 2021-2050. For the intermediate period of 11 years (from 2010 – 2020), we use observations from the 1960-1970 period. For the period 2021-2050, we use the AMMA2050 bias-corrected data for 29 Coupled Model Intercomparison Project 5 (CMIP5) global climate models over Africa (see Supplementary Information Table 2). In the AMMA2050 project this dataset is developed by applying the Cumulative Distribution Function transform (CDF-t) method to derive information at 0.5° x 0.5° spatial resolution. This method, developed by Michelangeli et al. (2009), has been used to correct diagnostics of humidity (huss), surface temperature (tas), surface maximum temperature (tasmax), surface minimum temperature (tasmin), shortwave radiation (rsds), and surface winds (sfcWind), while an updated version of CDF-t (Vrac, 2016) method is used for bias-correcting rainfall. Famien et al. (2017) present a detailed description, validation and applications of AMMA2050 data and show that the CDF-t method is effective at addressing biases. In order to extract data for the 35 LMSRB catchments from the AMMA2050 bias-corrected data, we use a bilinear interpolation method, interpolated at horizontal grid resolution of 0.05°, followed by the application of individual catchment shapefiles. These are to-date the most comprehensive bias-corrected high resolution future climate projections for the region, with the catchment-derived projections able to provide spatially explicit differences within the basin. We force the WEAP model using the 29 CMIP5 model climate projections, whilst keeping other aspects constant (e.g. barrage operation is held constant at 375 cumecs) to assess the sensitivity of the system to climate change, especially rainfall change.

For land-based future ET_0 projections, we use the Penman-Monteith method to calculate mean (average for the 2021-2050) monthly values. For the calculation we use relevant input data from the AMMA2050 future climate projections (see Supplementary Information Figure 4). The calculation of net evaporation is based on reference lake evaporation (using data for Nkhata Bay as proxy for the lake as this meteorological station is closest to the Lake) and monthly rainfall over the lake (using land-based rainfall for Nkhata Bay). We maintain consistency with this calculation, by using reference evaporation values for the same catchments and rainfall over the lake obtained from future climate projections, to calculate net evaporation over the lake.

3. Results

3.1. Model performance

The model shows reasonable ability to capture the streamflow patterns for the Bua catchment, the largest lake inflow catchment and the one with the most consistent streamflow data (Supplementary Information 6), especially for the long-term runoff. In the absence of a groundwater component and the rainfall-runoff modelling assumption that all processes occur in the same monthly time step, the model shows limited ability to capture baseflow during the dry season. However, the sparse and inconsistent observed streamflow record makes calculating goodness of fit statistics difficult; one of the reasons why a manual calibration is chosen. The model simulates lake levels satisfactorily (Figure 5) despite the absence of a groundwater component, with a relatively low root mean square error (RMSE) and ratio of root mean square error and standard deviation (RMSE-RSR) (Chen et al. 2012; Moriasi et al. 2015). While it captures seasonal variation well, the model is less able to capture inter-annual variability (lower Nash-Sutcliffe Efficiency values). Applying changes in reservoir operation rules over time improves the model performance. There is a slight under and over simulation of lake level during certain periods, but overall the model simulates the water balance reasonably well as indicated by the low percent bias. The simulation of flow downstream of the lake is more difficult to capture (see Supplementary Information 5) particularly because small differences in simulated lake levels mean large changes in downstream flows. The model is better able to capture long-term streamflow variations (annual and multi-year) compared to the monthly time scale.

3.2. Lake Malawi contributions by country

The catchment area of Lake Malawi covers parts of Malawi, Tanzania and Mozambique (Figure 1). During consultations, stakeholders across different sectors showed concern regarding the contribution of inflow from the different countries, particularly the high contribution by the Ruhuhu basin in Tanzania. This basin receives high rainfall (in relation to the lake basin), has relatively low population density and limited water use for irrigation, leading to higher inflows into Lake Malawi. We analyse the model-based contribution from catchments from each of the three countries (Figure 6), excluding rainfall over the Lake Malawi surface. We find that over the 50 year period (1960 – 2009), Malawi contributes ~55%, Tanzania contributes ~41%, and Mozambique contributes ~4% to the total inflow. These values are approximations because the Mozambique and Tanzanian catchment inflows are based on rainfall interpolated from gauges located in Malawi using Thiessen Polygons (See Section 2).

There is considerable variability in country-wise contributions, but no systematic change over time. While for some years, the Tanzanian contribution is more than 50% (e.g. 1972 and 1992), the contribution from Malawi dominates for most years. The high contribution from Tanzania suggests that concern expressed by stakeholders regarding changes in inflows from Tanzanian is reasonable, given that Tanzania has plans to expand irrigated agriculture in those catchments. The Southern Agricultural Growth Corridor of Tanzania (SAGCOT) which earmarks substantial areas for irrigation expansion includes the Ruhuhu catchment within the SAGCOT Ludewa cluster (see http://sagcot.co.tz/). Malawi also has plans to expand irrigation through the Green Belt Initiative (Govt. of Malawi 2011) which would lead to consumptive use of Lake Malawi inflows or water from the lake directly. There is also on-going cooperation between Malawi and Tanzania to share water resources of the Songwe River, which forms their border, using two multi-purpose dam projects to expand irrigated agriculture. Inflow from Mozambique is relatively low, but there are no published plans to expand irrigated agriculture in the region to date.

3.3. Climate change impacts

Figure 7 shows the potential effects of climate change (rainfall and evapotranspiration on land) on lake levels without considering changes in the operating rules for the Kamuzu barrage. There is a wide range in impacts which reflects the large differences between climate model projections of rainfall change. As the lake aggregates the catchment rainfall-runoff response, future lake level changes largely mirror future rainfall changes. These changes can be summarised as three unequal size groupings of projections; (i) high lake levels, (ii) lake levels within the range of recent observations, and (iii) low lake levels including instances with levels falling below the LMOT. For certain model projections, lake levels rise sharply to reach maximum modelled levels (480 masl), after which unrestricted downstream flows occur (effectively reservoir overtopping). Under such conditions, extremely high downstream flows could lead to periodic or persistent flooding, because observed discharge in the Lower Shire, at the Chiromo gauging station (confluence of Shire and Ruo rivers) has historically been associated with high lake outflows. For instance, for the three-year period from 1979-1981 (observations), barrage outflows exceeded 900 m^3/s in April-May-June, and led to lower Shire flows exceeding 1000 m^3/s. For nine climate model projections, the model simulates barrage outflows exceeding 1000m^3/s for duration ranging from 1 – 28% of the simulation period (30 years), showing that high lake levels and overtopping can lead to extremely high outflows. While this result increases understanding of future risks, a more detailed flood risk model would help better understand the consequences associated with such high peak daily flows.

Within (ii), for some climate projections lake levels remain moderately high, meaning that barrage operation could provide consistent flows for downstream requirements. However, for some projections, lake levels remain higher than the LMOT, but show a consistent reduction. Under such conditions, downstream releases could be constrained, leading to the risk of insufficient water downstream to sustain current and potential future hydropower and irrigation requirements. Such changes in the risk profile, particularly in relation to hydropower reliability, would require adoption of risk management measures to minimize hydropower impacts over the different timescales. Within (iii) lower rainfall leads to lower lake levels, which for 11 projections leads to breaching of the LMOT at which point lake outflows stop and effectively change the Shire River from a perennial to a seasonal river. For several projections sustained decline in rainfall leads to lake levels falling persistently below the LMOT. In some cases lake levels after reaching the LMOT, remain just below it for an extended duration without substantial recovery or further decline in lake levels. The latter climate projections have two characteristics; just enough rainfall to maintain lake levels with no or little outflow, and lower long-term rainfall variability. Future lake level changes and frequency of reaching of critical thresholds show sensitivity to two factors; long-term rainfall changes and rainfall variability. This is partly because the lake aggregates the rainfall-runoff response from its catchments, minimising the effect of spatial differences in future rainfall patterns. While future climate change-driven lake levels are uncertain, results suggesting breach of the LMOT represent significant risks to downstream infrastructure, particularly hydropower reliability during the dry season.

4. Discussion

The LMSRB system is subject to important hydro-meteorological data constraints (Mwale et al. 2012) that mean there are choices and assumptions in model design that have a bearing on the intended modelling objectives. While the input data used in this study are the most comprehensive currently available, they have significant spatial and temporal gaps. Therefore, gap-filling and extensive interpolation in some areas (e.g. in the mountainous regions of Tanzania) was required to develop a 60 year rainfall dataset for the Lake catchment through the NWDP II. Data gaps also exist in lake rainfall and lake evaporation. Model calibration in such data scarce areas is challenging because of sparse streamflow observations, which limits the model's representation of hydrological processes. Overall, we have much greater confidence in the model's ability to simulate lake levels over annual and multi-year timescales than streamflow for specific lake tributaries and intra-annual timescales. The size and extent of the lake buffers the variability of catchment inflows and the calibration process provides a reasonable representation of Lake Malawi levels at a monthly time step

(Figure 6). The model is reasonably suitable for simulating the implications of future climate change for lake levels, which requires assumptions about the future barrage operation.

Choices in the modelling approach also require consideration; for instance, use of 1960-1970 observed climate for the intermediate 2010-2020 period. A sensitivity analysis of different datasets (historical proxies, gridded datasets etc.) is beyond the scope of this research, but we note that the choice of the period used to start the model from does have an effect on the starting point of the future simulations in 2021. The model projections cover a wide range of possibilities, from very high lake levels to very low lake levels (including breach of the LMOT). The results incorporate an important assumption; that lake evaporation rates in the future do not change. However, lake evaporation could increase with increasing temperatures, as seen elsewhere (USGS 1986; Lenters et al. 2013; Vanderkelen et al. 2018a, b) or decrease, depending on the combination of changing cloud cover and lake rainfall; this is an important source of uncertainty.

Multiple consultations with stakeholders informed model design and helped define the core objectives of the study. In a data constrained region, using a model co-production approach was crucial to capture the history and timing of operational decisions to increase the model representativeness for this lake-basin system. Besides being able to develop a model that addresses relevant concerns of stakeholders, customising the modelling approach helped enhance interest, gain acceptability and trust, and increase the shared ownership of the model. With further development, this model could be used for scenario analysis to examine different dimensions of water, energy and food security concerns in Malawi. The model is intended to be transferrable to enable stakeholders to continue its use.

This study shows that the breach of a hard threshold (LMOT) is a possibility and furthermore there are considerable risks of downstream flooding under higher lake levels and outflows. Climate change impacts on power generation of run-of-river hydropower plants, which use the natural flow of the river, are region-specific and necessitate in-depth assessment of individual case studies (Schaefli 2015), especially in threshold-affected basins like the LMSRB. Moreover, cessation of lake outflows would reduce Shire River dry season flows, and could significantly affect supplementary irrigation supply for existing sugarcane cultivation in the Lower Shire River Basin. A crucial insight that emerged during stakeholder consultations was one of conflicting management priorities about outflows. For instance, hydropower stakeholders needed a specific consistent flow to produce power at peak capacity, which was different to the barrage operator's assessment because the operator was concerned about sedimentation upstream of the hydropower plants at this volume of flow. The WEAP model described here can incorporate infrastructural plans (hydropower, irrigated agriculture, urban water supply, etc.) and their water requirements to improve the relevance of future assessments – further work aims to explore more comprehensively the combined risks of future changes in climate and non-climate factors, particularly the implications of alternative LMSRB development pathways.

5. Conclusions

This study presents a water resources model developed with stakeholder input that simulates the unconventional hydrology of the Lake Malawi Shire River Basin. The model is a significant improvement over previous water balance models of the system because it simulates hydrology and inflow of contributing catchments, lake water balance and infrastructure management decisions, making it more suitable for scenario analysis. In the observed period, model simulations indicate substantial contributions from catchments in Tanzania to Lake Malawi, underscoring the importance of transboundary linkages in this basin. The model simulates a wide range of Lake Malawi levels under potential future climate conditions, as projected by 29 bias-corrected global climate models, reflecting the wide range of future rainfall changes. Potential future outcomes range from major downstream flooding to no Lake Malawi outflows to the Shire River.

While the model simulates this unconventional lake-basin system reasonably well, limitations associated with data availability and choice of modelling approach, as with other modelling studies, are important to interpret the results (see section 4 – Discussion). Climate change poses risks to Malawi's water, energy and food security, because the Lake Malawi Shire River Basin sustains much of its hydropower and irrigation, along with domestic water supply, and environmental requirements. The model can be used to explore risks to on-going infrastructure expansion plans in Malawi under future water availability and demand changes. The operation of the Kamuzu Barrage is of critical importance for managing water resources, and future work should assess the robustness of different operational rules to provide contingency plans for highly uncertain future conditions.

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Figures

Figure 1 – The Lake Malawi Shire River Basin (LMSRB) location and topography developed using the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Digital Elevation Model (DEM). The Lake Malawi outflows into the Shire River towards the south, and the Shire River flows south and joins the Zambezi in Mozambique. Lake Malombe; a shallow lake, forms part of the upper Shire River Basin. The LMSRB covers most of Malawi, and parts of Tanzania and Mozambique. The.

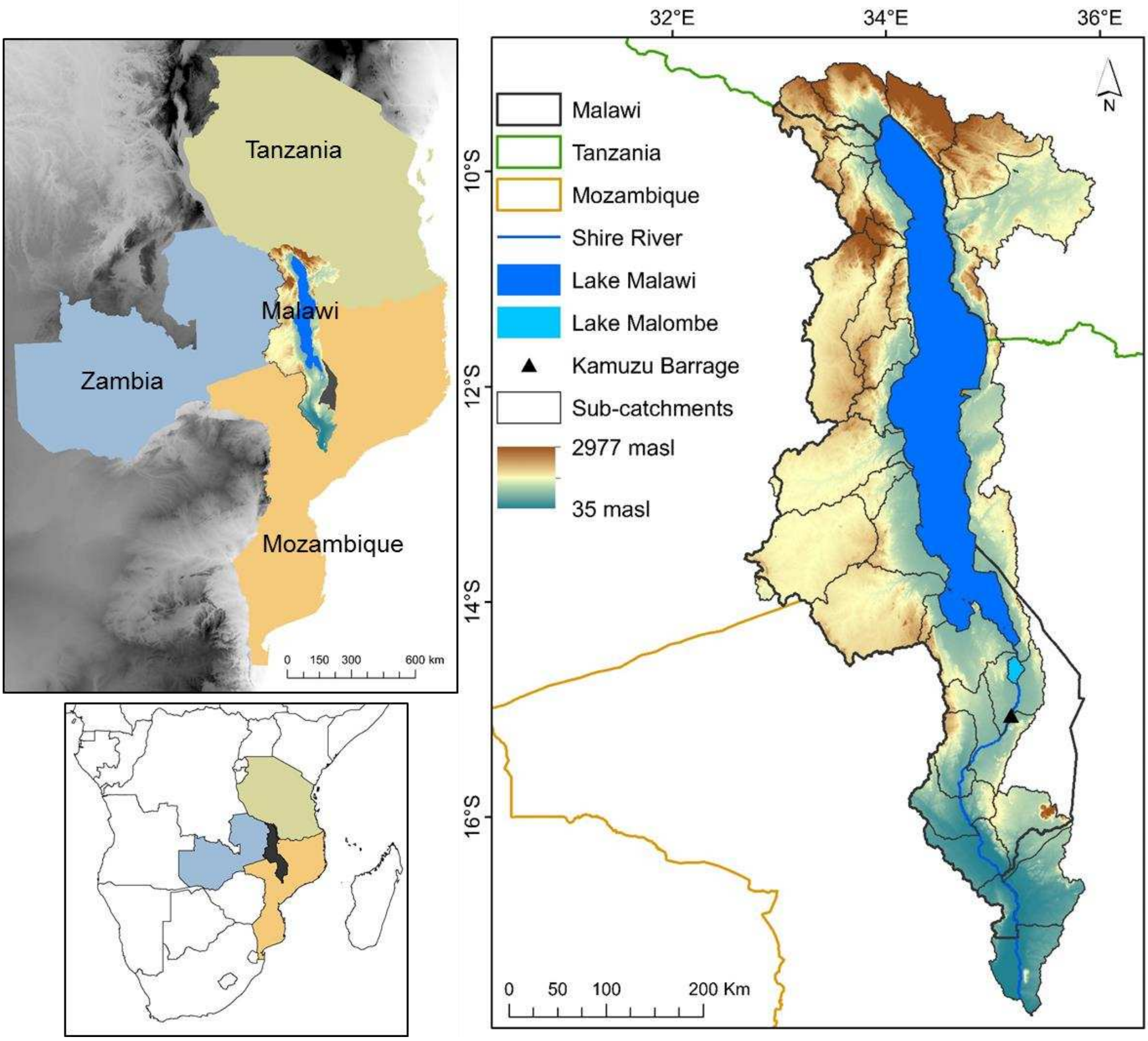


Figure 2 - Elevation profile of the Shire River, starting from the Lake Malombe (Figure 1 light blue), indicates three distinct stages; upper Shire which includes the Kamuzu Barrage, the middle Shire which includes the three hydropower stations and the lower Shire which includes the irrigated area along the right bank and the Elephant Marsh wetland.

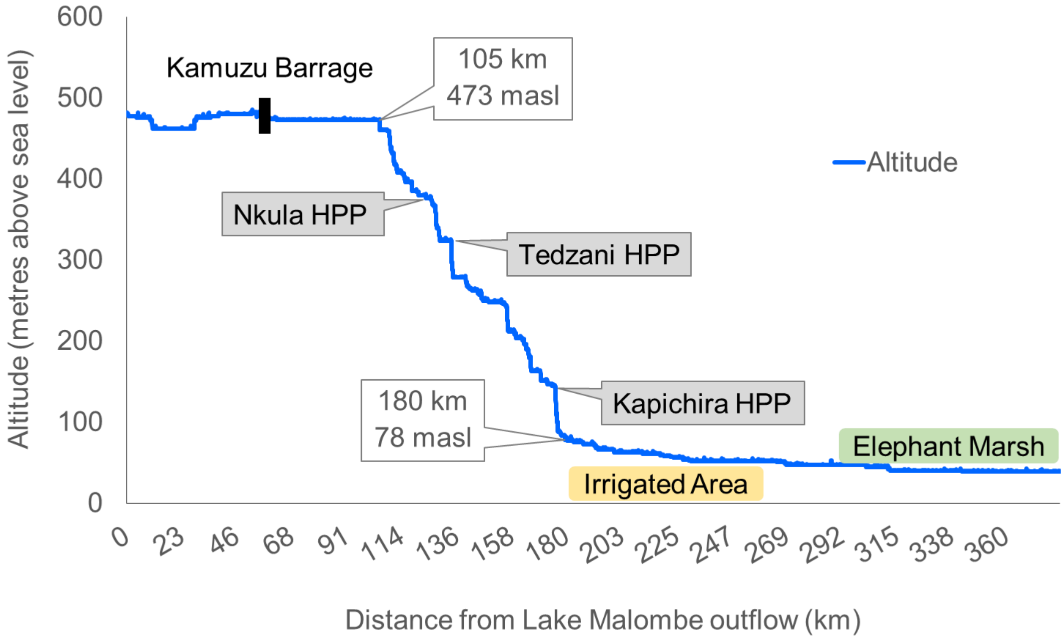


Figure 3 – Lake Malawi levels (1921-2018) and Shire river streamflow at the Kamuzu Barrage (Liwonde gauging station) (1948-2009)

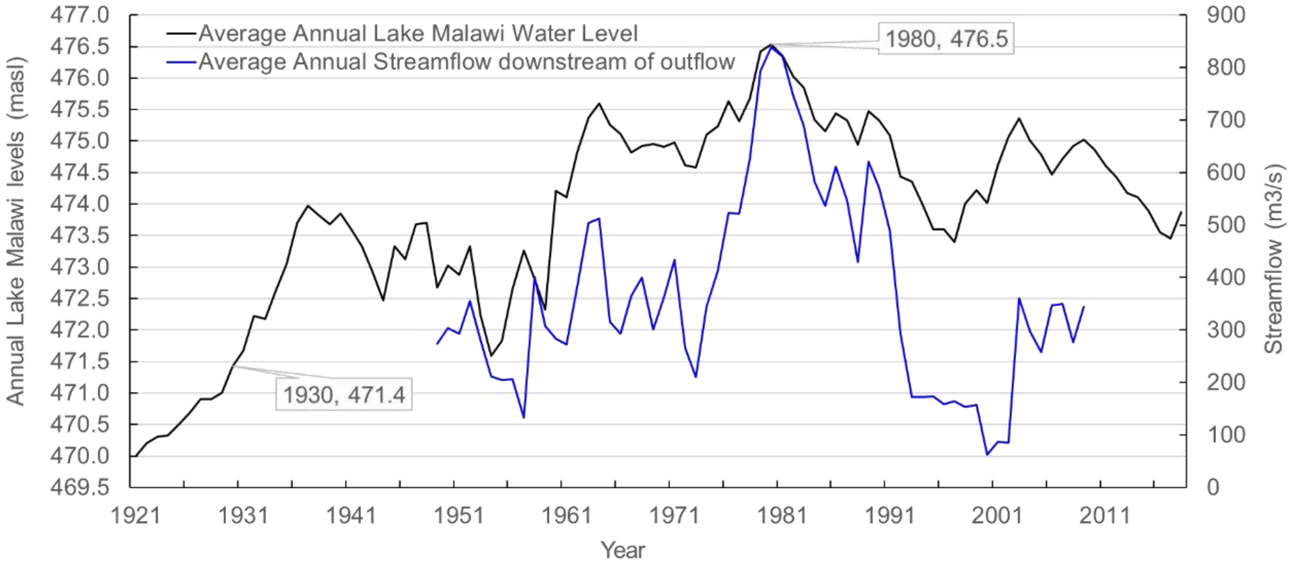


Figure 4 – WEAP model schematic for the LMSRB representing the catchments delineated in the digital elevation model (left). Model structure includes catchment nodes, Lake Malawi reservoir node, flow requirement downstream of the barrage (termed Release), three existing hydropower stations etc. Lake Malawi catchments inflow into the ‘Routing River’ which flows to the reservoir node. Lake Malawi’s largest catchment; Bua, is highlighted in a red box.

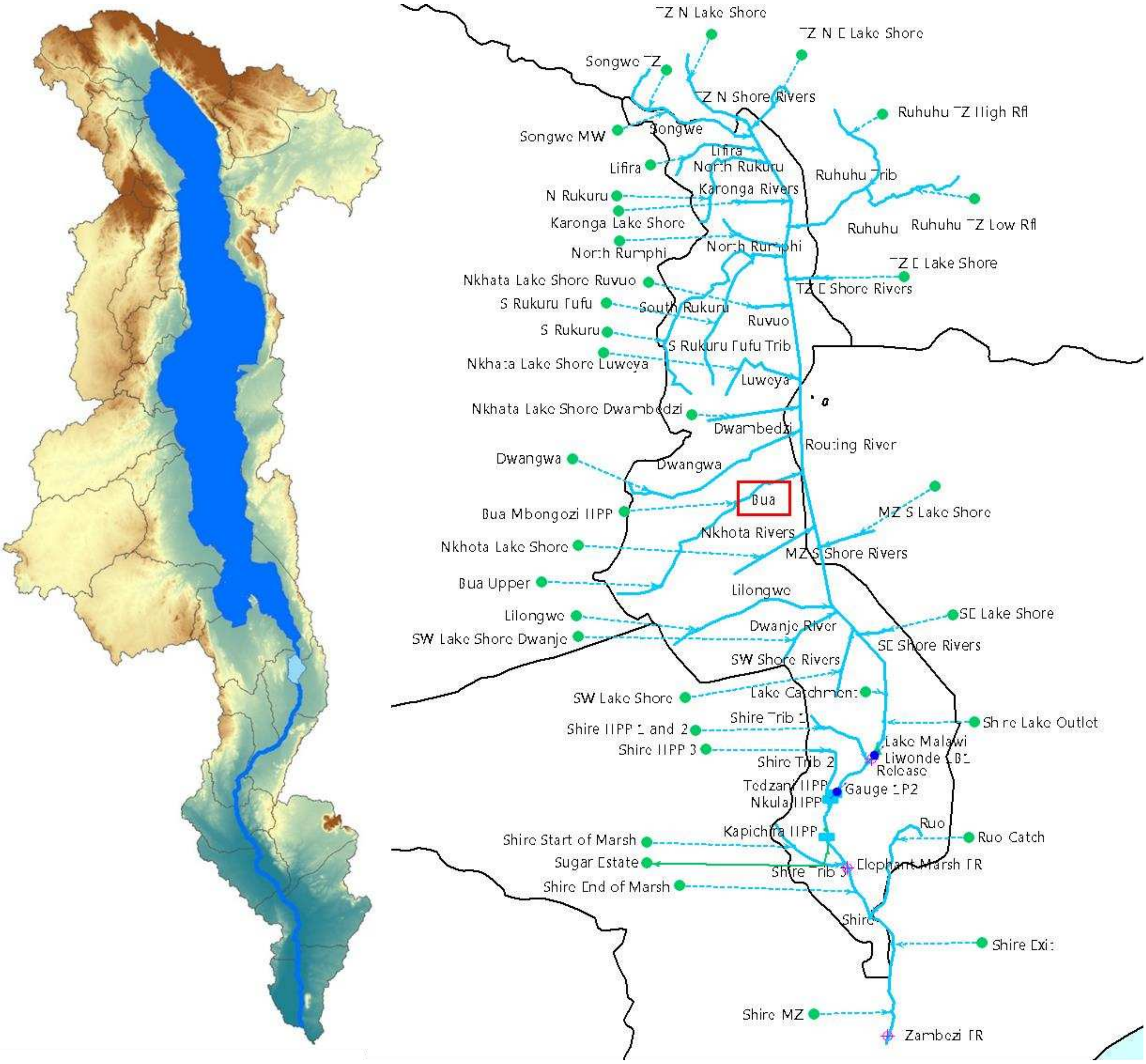
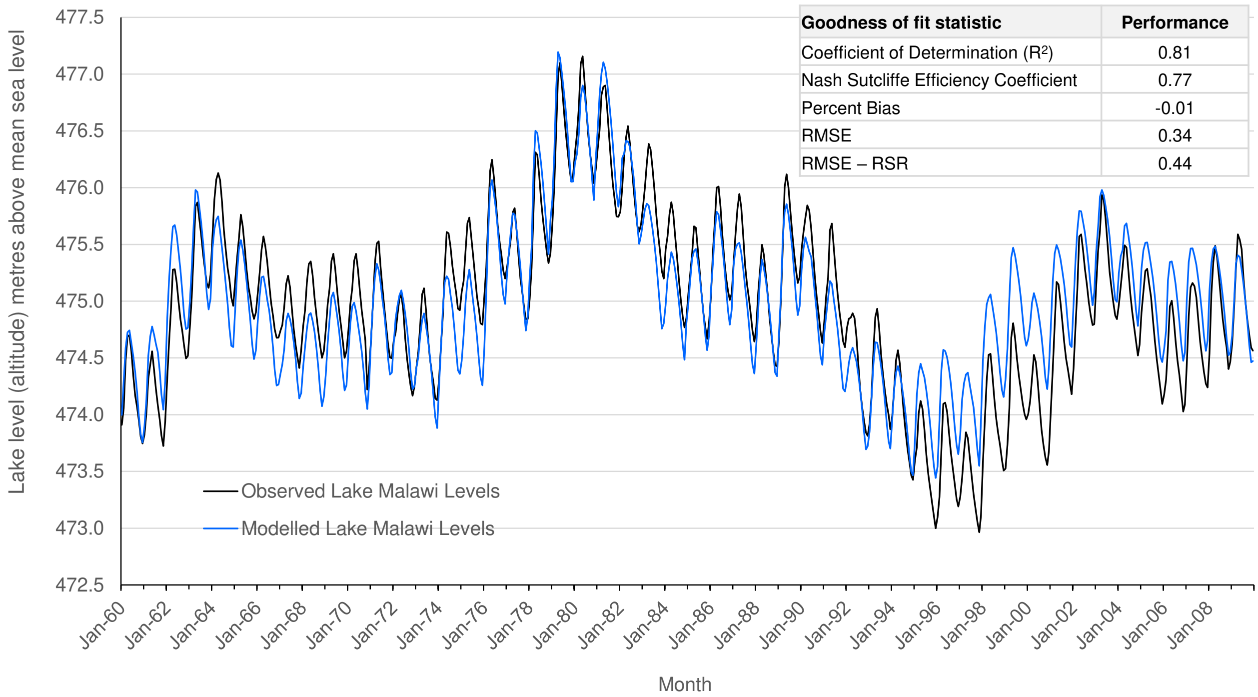


Figure 5 – Observed and simulated monthly Lake Malawi levels for the period 1960-2009 with inset of table showing goodness of fit statistics indicating model performance.



Goodness of fit statistic	Performance
Coefficient of Determination (R^2)	0.81
Nash Sutcliffe Efficiency Coefficient	0.77
Percent Bias	-0.01
RMSE	0.34
RMSE – RSR	0.44

Figure 6 – Simulated contribution of Lake Malawi tributary inflows from Malawi, Tanzania and Mozambique

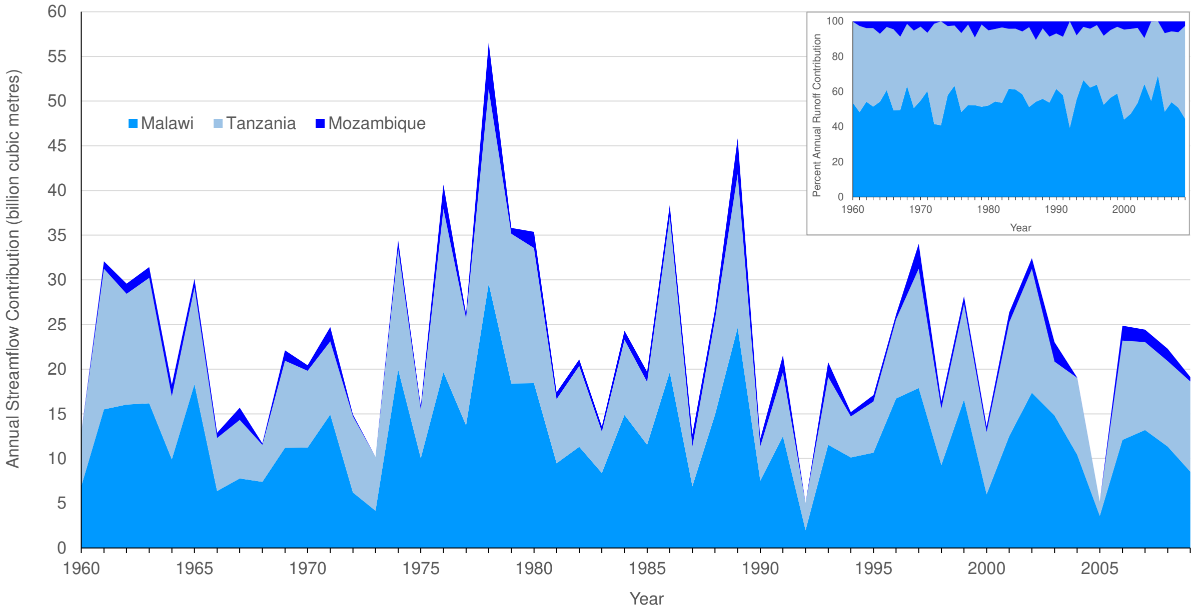
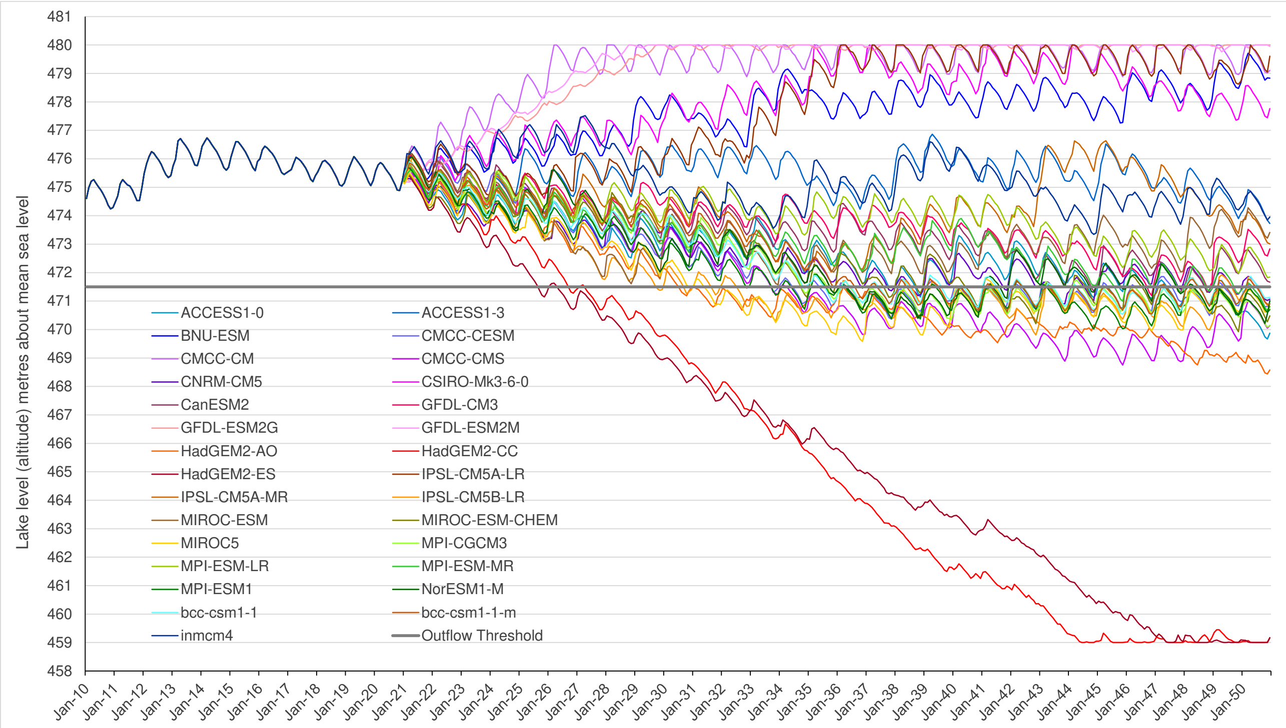


Figure 7 - Climate change impacts on Lake Malawi levels based on future climate projections from 29 bias-corrected CMIP5 models. 471.5 masl (marked by grey line) indicates the LMOT, while coloured lines indicate lake levels for different model projections.



Tables

Table 1 – Formulation of Lake Malawi as a reservoir: Rationale and assumptions

Reservoir formulation in WEAP	**Rationale**
Reservoir extent	The Kamuzu barrage functions as a dam, and the reservoir extends upstream of the Kamuzu barrage. This includes Lake Malawi, Lake Malombe (Figure 1), and a part of the Upper Shire basin. We assume this to simplify reservoir formulation and to also reflect the hydrological connectivity of the Lake Malawi, Lake Malombe and the river section upstream of the barrage.
Lake levels from 460 to 481 masl	The lake levels over the past ~200 years have fluctuated between these levels, so for the timescale of this analysis (multi-decadal) this range is considered suitable. Reservoir storage volume starts at 0 km^3 at 460 masl, and linearly increases to 646.8 km^3 at 481 masl. The upgraded barrage can regulate lake levels up to 477masl. When lake levels exceed this level there is overtopping.
Volume elevation curve	In the absence of an observed relationship we use a linear relationship consistent with observations developed by Lyons et al. (2011) to estimate lake volumes at different lake levels.
Loss to groundwater	Groundwater recharge component in the lake water balance is neglected due to lack of observations (see also Kumambala and Ervine, 2010)
Maximum hydraulic outflow from the Kamuzu barrage (cumecs)	Based on observed discharge (releases) at Kamuzu barrage, three periods with different characteristics are used. From 1960-1993 monthly maximum hydraulic outflow ranges from 575 in September to 735 in March. From 1994-2002, outflow is restricted to 200, while from 2003-2050 outflow is restricted to 375 cumecs.
Top of inactive zone	Inactive zone is defined at the LMOT (471.5 masl or 352.8 km^3 storage). This effectively means that water below this level is not available for release from the barrage.
Top of buffer zone	Water released when reservoir levels are in the buffer zone is regulated by the buffer coefficient. We define the buffer zone from 471.5 masl / 352.8 km^3 to 474 masl / 441 km^3, when water is released at a restricted rate.
Buffer coefficient	A 0.95 buffer coefficient is used to restrict flows when water levels are in the buffer zone. This marginal restriction is assumed to reflect to some extent the changed priority of maintaining lake levels that emerged after low Lake Malawi levels in 1993.
Maximum lake level	We use 475 masl / 470.4 km^3 as the maximum level because above this, levels are high enough to cause potential floods around the lake, reflecting the concerns of stakeholders regarding extensive flooding as seen during the 1979-80 period.