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Climate Change Impacts on Low-Flows in Maha Oya River Basin, Sri Lanka: Implications for Domestic Water Security

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Abstract: Water security in small island developing countries like Sri Lanka is increasingly threatened by climate change and anthropogenic pressures. Maha Oya River, located in the intermediate climatic zone of Sri Lanka, is a vital water source for over four million people who face increasing water demand and hydrological stress. Despite its socio-economic centrality, the basin's hydrological sensitivity to climate change remains inadequately quantified by scientific research. Therefore, this study assessed the climate-driven dynamics of low-flows in the Maha Oya River basin by a hydrologic modelling approach coupled with future rainfall projections to evaluate the adequacy of low flows for planned potable water extractions. HEC-HMS hydrological model was calibrated and validated using observed streamflow data at Giriulla and Badalgama from 2009 to 2018, with goodness-of-fit values falling within acceptable ranges. The study utilized NASA NEX-GDDP CMIP6 dataset and HadGEM3-GC31-LL and CESM2 Global Climate Models (GCMs), under SSP245 and SSP585 scenarios, to project future rainfall, with bias correction conducted using the Quantile Delta Mapping (QDM) method. The calibrated HEC-HMS model was used to simulate the future streamflow across near-future (2019–2049), mid-future (2050–2074), and far-future (2075–2099) periods. Low-flow trends, defined by the 90-100% flow exceedance percentiles, were identified across all projected time periods and evaluated against anticipated potable water abstraction demands. Results revealed severe reductions in low-flow conditions, with decreases of 90–100%, anticipated by the end of the 21st century under both scenarios. Key intake locations, including Mawanella-Kappagoda and Hemmathagama, faced persistent near-zero flows, jeopardizing planned extractions (333,230 m^3/day by 2040). Deficits were intensified under SSP585, with the CESM2 projecting 100% loss of low flows by mid-century. While upstream zones demonstrated transient recovery, downstream regions exhibited irreversible drying. The proposed expansions in potable water extractions at Rambukkana (22,000 m^3/day) and Hemmathagama (24,200 m^3/day) significantly exceeded projected availability, risking supply-demand imbalances during critical dry periods. This study underscores the urgency of adaptive strategies such as managed aquifer recharge and demand governance to mitigate water insecurity. Furthermore, the study contributes to the development of a methodology that integrates CMIP6 projections into basin-scale hydrologic modelling, providing broadly applicable insights for assessing climate-impacted water availability in tropical catchments.

Keywords: Global climate model, HEC-HMS, Low-flow projection, Maha Oya River basin, NASA NEX-GDDP CMIP6, Potable water extraction

1. Introduction

Water security, a fundamental pillar of sustainable development, is imperilled globally by escalating population growth, industrialization, and climate-induced disruptions in hydrological patterns [1]. Small island developing countries, including Sri Lanka, exhibit increased vulnerability due to geographic constraints, economic dependency on climate-sensitive sectors, and exposure to compounding risks such as sea-level rise and intensified hydro-climatic extremes [2].

The Maha Oya River basin, which is a critical water source for domestic, agricultural, and ecological sectors, epitomizes the water related challenges in Sri Lankan catchments. The basin experiences heterogeneous hydrological regimes due to dual climatic zones (intermediate and wet), with bimodal monsoon peaks — the southwest monsoon (May to September) and the

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northeast monsoon (December to February) — punctuated by prolonged dry periods from January to March and July to September. Unsustainable sand mining, groundwater over-extraction exceeding recharge rates by 30%, and surface diversions for agriculture have reduced dry-season base flows by 40% since 2000, degrading aquatic ecosystems and water quality [3], [4]. Concurrent deforestation, which has resulted in a 23% loss since 2000, and urbanization, which has increased impervious surfaces by 18%, have diminished infiltration capacity, amplifying runoff variability and reducing groundwater recharge [5]. Moreover, the Maha Oya River Basin Water Security Assessment Report [6] classified the Maha Oya as a 'high-stress' river basin.

National Water Supply and Drainage Board (NWSDB), Sri Lanka's prime and sole authority for provision of clean and safe pipe-borne potable water, operates nine intakes along the Maha Oya. It is the third largest water source for the NWSDB, extracting 17.08 Million Cubic Meters (MCM) annually [7]. Planned expansions aim to increase extraction to 121.63 MCM per year by 2040 through 17 intakes, serving 4.3 million residents [8]. However, system reliability is compromised during the low flow from January to March and July to September, when intake capacities decline. These challenges are compounded by elevated turbidity and aging infrastructure [7], making the provision of potable water increasingly difficult. Despite its socio-economic centrality, the basin's hydrological sensitivity to climate change remains inadequately quantified by scientific research. Existing studies focus on historical trends rather than future low-flow dynamics under evolving emission scenarios, which represent a critical gap that this study primarily addresses. Therefore, this study assessed the climate-driven dynamics of low-flows in the Maha Oya River basin by a hydrologic modelling approach coupled with future rainfall projections.

HEC-HMS, Hydrologic Engineering Centre-Hydrologic Modelling System model [9] is one of the widely used physically based models applicable to a wide range of situations and its parameters describe a catchment's physical characteristics. For the catchments with dendritic drainage patterns, such as the Maha Oya River basin, HEC-HMS model has been recommended as the most appropriate hydrologic modelling tool [10]. It enables distributed outputs at fine spatiotemporal resolutions, integrating known hydrological physics to conceptualize rainfall-runoff dynamics [11]. HEC-HMS has been utilized in this study to simulate rainfall-runoff processes across three periods: near-future (2019–2049), mid-future (2050–2074), and far-future (2075–2099).

Future climate projections in this study were based on NASA's NEX-GDDP CMIP6 dataset, which effectively reproduced accurate projections of future precipitation and temperature [12], [13]. Quantile Delta Mapping (QDM) bias correction method was used to minimize precipitation discrepancies while adjusting distributional mismatches, which is essential for accurate low-flow simulation [14]. The two Global Climate Models (GCMs) selected for this research, HadGEM3-GC31-LL and CESM2, are recognized for their effectiveness in simulating low-flow conditions [15], [16]. Moreover, this study used the Shared Socio-economic Pathways SSP245 and SSP585, which represent mid-range and high-level climate scenarios widely used in similar studies to assess future streamflow.

The objectives of the study are to set up the HEC-HMS hydrological model for the Maha Oya basin, generate future rainfall projections, and assess model-predicted future low flows against NWSDB water requirements across three time horizons: near-future (2019–2049), mid-future (2050–2074), and far-future (2075–2099). By integrating hydrologic modelling, climate science, and water management, this study provides actionable insights for policymakers to support equitable and sustainable water access amid increasing climatic-related uncertainties.

2. Materials and Methodology

2.1 Study Area

The Maha Oya River basin, located in western Sri Lanka (7°10'-7°40'N, 79°50'-80°30'E), spans about 1,467 km^2 and stretches approximately 130 km from the western bank of the hill country at Dolosbage near Nawalapitiya to the Indian Ocean at the 'Kochchikade', along the western coast. It gathers flows from 21 tributaries along its path [17]. The river traverses five districts: Kandy in the Central Province, Kegalle in the Sabaragamuwa Province, Kurunegala and Puttalam in the Northwestern Province, and Gampaha in the Western Province.

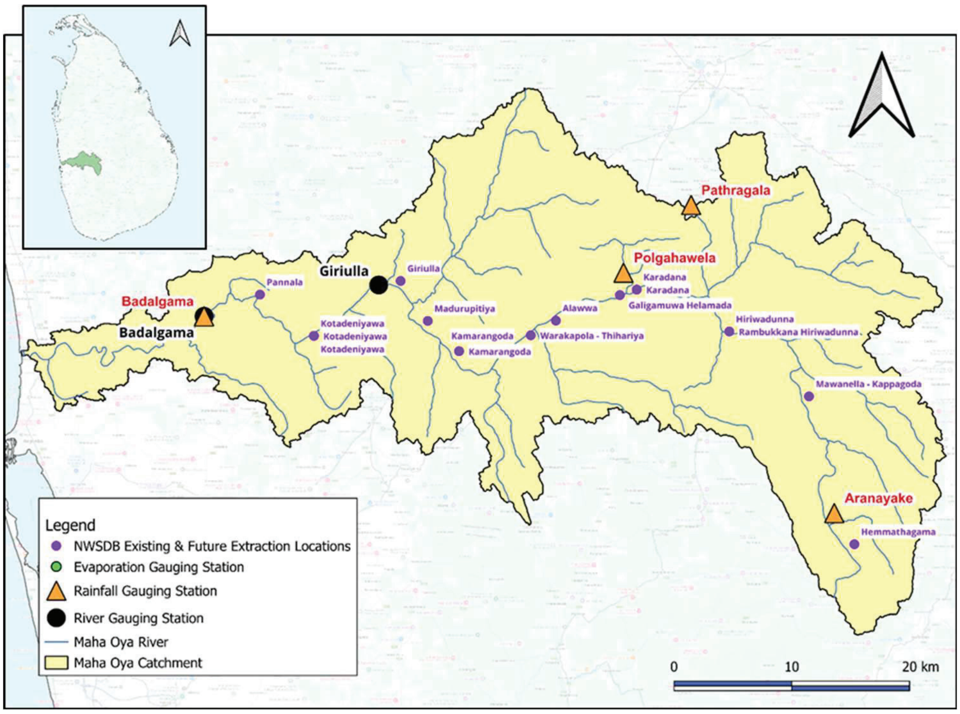

Figure 1 - Study area's spatial configuration, gauging stations, NWSDB's existing and future water extraction locations and delineated stream network

It features a dendritic drainage pattern shaped by steep slopes in the upper reaches (elevations >1,500 m) and gentle plains in the lower regions (near sea level). The basin experiences a tropical monsoon climate, with annual temperatures averaging 25-32°C and bimodal rainfall (2,000-3,000 mm per year) driven by southwest (May-September) and northeast (December-February) monsoons. Seasonal flow variability is pronounced, with peak discharges during monsoons and reduced flows in dry periods. Land use is diverse: forested uplands transition to agricultural zones (tea, rubber, and paddy) and densely populated urban areas (Gampaha). The river is ecologically vital, providing water for domestic, agricultural, and industrial use, but it faces stress from urbanization, sand mining, and pollution.

2.2 Datasets and River Network Generation

Daily rainfall data spanning a 10-year period (2009–2018) were obtained from four gauging stations within the Maha Oya River basin, Sri Lanka: Aranayake (7.15°N, 80.47°E), Badalgama (7.30°N, 79.98°E), Pathragala (7.39°N, 80.37°E), and Polgahawela (7.33°N, 80.30°E), from the Department of Meteorology, Sri Lanka. River discharge data for the same period were obtained from the Department of Irrigation, Sri Lanka for Giriulla (7.27°N, 80.10°E) and Badalgama (7.17°N, 80.03°E) gauging stations. Monthly pan evaporation data for the Bathalagoda station (7.53°N, 80.43°E) were sourced from the NWSDB. The density of gauging stations for rainfall, river discharge, and evaporation were evaluated against the World Meteorological Organization's (WMO's) station density guidelines and found to be acceptable.

Land use data were sourced from the GlobCover USGS 2009 dataset, which was validated in prior regional studies [18]. Soil parameters were derived from the Food and Agriculture Organization (FAO) Digital Soil Map of the World [19], [20]. Terrain data, which contain 1-arc second Digital Elevation Model (~30 m resolution), was downloaded from USGS Earth Explorer, an online search, discovery, and ordering tool developed by the United States Geological Survey (USGS). These catchment physiographic data were used to derive the relevant hydrologic input parameter values of the model. Catchment delineation was carried out using the HEC-HMS based on the breakpoints at the NWSDB water extraction locations (9 existing and 8 planned intakes across 12 locations), river gauging stations, and the Maha Oya River outlet. Stream network generation integrated these breakpoints ensuring the alignment with basin hydrography. The weighted areal rainfall was computed using the Thiessen polygon method. The basin slope for the derived sub-basins varies from 0.06 to 0.36. Figure 1 illustrates the study area's spatial configuration, including rainfall, river discharge, and evaporation gauging stations, NWSDB's existing and future water extraction locations, and the delineated stream network.

2.3 HEC-HMS Hydrological Model

2.3.1 HEC-HMS model setup

The Hydrologic Engineering Centre-Hydrologic Modelling System (HEC-HMS) integrates basin, meteorological, and control specification components. The basin model, encompassing canopy, surface, loss, transform, routing, base flow, and evaporation sub-models, simulates streamflow by translating atmospheric inputs [9]. Herath and Wijesekera [4] presented that the combination of these sub-models was effective in simulating the streamflow behaviour of the Maha Oya River basin. The meteorological model employs Thiessen polygon-derived gauge weights for spatially resolved precipitation estimation. The control specification defines the simulation of temporal parameters. In this study, initial parameters were derived from catchment physiography, followed by optimization via iterative calibration.

2.3.1.1 Canopy model

The simple canopy method has been adopted for the study. It simulates vegetation interception by retaining precipitation until the maximum storage (mm), which is defined using the GlobCover USGS 2009 land-use classification and calculated through ArcGIS zonal statistics. Initial storage was set to 0%, with the 'Simple' uptake method. Given the robust foundation provided by the GlobCover USGS 2009, the initial parameters remained unchanged during the optimization process.

2.3.1.2 Surface model

The simple surface method has been used, where it simulates soil surface processes by retaining precipitation until the maximum storage capacity (mm) is reached, which is determined via sub-basin slopes (0.06-0.36 m/m) linked to slope-dependent storage values (1-50.8 mm). Initial storage was set to 0% (dry conditions). Infiltration occurs pre-saturation; runoff arises when capacity is exceeded. Given that the basin slopes have been derived from reliable USGS Earth Explorer terrain data, the initial parameters were kept unchanged during the optimization trials.

2.3.1.3 Loss model

The loss methods calculate the quantity of water contributing to the runoff in the river for each time interval in the modelling cycle [21]. Among the different precipitation loss methods available in the HEC-HMS, deficit and constant loss model was selected for this study, which is designed to perform continuous-based simulations. It simulates infiltration by separating precipitation into runoff and constant-rate infiltration after satisfying an initial soil moisture deficit. The initial deficit and maximum deficit parameters were derived from porosity and field capacity. Constant Rate (mm/hr) reflected soil-specific hydraulic conductivity.

2.3.1.4 Transform model

The HEC-HMS SCS Unit Hydrograph method models runoff using a dimensionless hydrograph based on lag time, calculated from time of concentration (Tc) using flow length, basin slope, and Curve Number (CN). CNs were derived from reclassified FAO soil data and GlobCover 2009 land use via Python and ArcGIS. Lag times, computed empirically, remained unaltered as simulations matched observed peak timing. Peak Rate Factor (PRF) was adjusted through calibration to align with hydrograph magnitudes.

2.3.1.5 Routing model

The HEC-HMS lag routing method simulates temporal delays in hydrograph propagation between river reach endpoints. Lag time, representing water travel duration, was initialized at 150 minutes per reach and calibrated to align simulated and observed peaks. Chosen for simplicity, this approach prioritized timing accuracy over hydrodynamic complexity, omitting storage and attenuation effects.

2.3.1.6 Base flow model

Recession base flow method was selected in this study to represent base flow generation, given its proven applicability in continuous process modelling in Sri Lankan catchments and its ability to produce the best fit against observations [11], [22]. It simulates base flow using an exponential decay equation ($Q_b(t) = Q_0 e^{-kt}$), where Q_0 is initial discharge and k is the recession constant. Parameters k and ratio-to-peak were calibrated to reduce base flow overestimation, aligning simulated recession limbs with the observed hydrographs. Initial values, based on regional groundwater characteristics, were refined through iterative trials. Adjusting k moderated the recession rate, while ratio-to-peak optimized recession phase initiation.

2.3.1.7 Evaporation model

Despite spatial uniformity assumptions, monthly evaporation approach effectively captured regional evaporation dynamics, balancing simplicity, and empirical accuracy. The uniform application ensured computational efficiency without compromising the representation of the hydrological cycle, as validated through model performance indices.

2.3.2 HEC-HMS model calibration, validation, and model performance evaluation

The HEC-HMS model was calibrated (2009–2013) and validated (2014–2018) using daily streamflow data at Giriulla and Badalgama stations. A combined manual-automatic calibration process iteratively refined the parameters in this continuous flow simulation. The goodness of fit between the observed and simulated hydrographs during calibration and validation was assessed through visual inspection and statistical indices: Nash-Sutcliffe Efficiency (NSE), Percent Bias (PBIAS), Coefficient of Determination (R^2), and Relative Standard Error (RSR). NSE quantifies residual variance relative to observed variance [Equation 1], with values ≥0.5 deemed satisfactory and 1 indicating perfect fit [23]. Recommended for long-term simulations [24], NSE evaluates temporal alignment of flow dynamics. PBIAS measures average systematic deviation between observed and simulated flows [Equation 2], where 0 denotes optimal performance. Negative/positive values indicate over/underestimation, with lower magnitudes reflecting higher accuracy [25]. R^2 [Equation 3] quantifies the proportion of observed variance explained by the model, ranging from 0 (no correlation) to 1 (perfect fit). RSR [Equation 4] normalizes root mean square error by observed standard deviation, where values approaching 0 signify minimal error. These indices collectively evaluated the model performance, with NSE and R^2 assessing predictive skill, PBIAS identifying bias trends, and RSR contextualizing error magnitude. Incorporation of these indices ensures comprehensive hydrological model validation [24].

To confirm the model's suitability for low-flow assessments, RSR was additionally evaluated for the 90–100% exceedance range over the 10-year calibration and validation period. This provided a focused measure of the model's accuracy during dry periods, essential for reliable future water availability projections.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Qobs,i - Qsim,i)^2}{\sum_{i=1}^{n}\left(Qobs,i - \overline{Qobs}\right)} \quad \dots (1)$$

$$PBIAS = 100\ x\ \frac{\sum_{i=1}^{n}(Qobs,i - Qsim,i)}{\sum_{i=1}^{n} Qobs,i} \quad \dots (2)$$

$$R^2 = \frac{SSR}{SST} \quad \dots (3)$$

$$SSR = \sum_{i=1}^{n}\left(Qsim,i - \overline{Qobs}\right)^2$$

$$SST = \sum_{i=1}^{n}(Qobs,i - \overline{Qobs})^2$$

$$RSR = \frac{RMSE}{\sigma_{obs}}\ \text{RMSE Stdev} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Q_{obs,i} - Q_{sim,i})^2} \quad \dots (4)$$

where $Q_{obs,i}$ is the observed discharge at time i, $Q_{sim,i}$ is the simulated discharge at time i, and n is the number of observations.

2.4 Flow Duration Analysis and Threshold Values for Different Flow Regimes

Flow Duration Curve (FDC) quantifies flow variability by plotting cumulative frequency against discharge, supporting hydrological assessment and water resource management. According to US EPA [26], flows are categorized as peak-flows (0–10% exceedance), intermediate-flows (10–90% exceedance), and low-flows (90–100% exceedance). This study focuses on the low-flow regime (90–100% exceedance), particularly the 95th percentile, which is critical for low-flow analysis and sustainable water resource planning in the Maha Oya basin.

2.5 Projection of Future Rainfall and Bias Correction

High-resolution future rainfall projections up to 2099 for the Maha Oya River basin were derived from the NASA NEX-GDDP CMIP6 platform [12], [13], utilizing outputs from the HadGEM3-GC31-LL and CESM2 global climate models under SSP245 and SSP585 scenarios. Data retrieval focused on four gauging station locations, Aranayake, Badalgama, Pathragala, and Polgahawela, over the historical period from 2009 to 2018, which was used for bias correction. Automated scripting via Windows CMD and curl commands streamlined the download of daily precipitation data, resolving spatial and temporal coverage challenges. To enhance robustness, an ensemble dataset was generated by averaging outputs from both models (HadGEM3-GC31-LL and CESM2), mitigating individual biases and uncertainties [14], [27]. Consolidated CSV files facilitated efficient integration into the HEC-HMS model, enabling simulations of future river flow dynamics. This approach ensured high-resolution, scenario-specific rainfall inputs critical for assessing low-flow impacts on potable water availability under climate change.

Bias correction was carried out using the QDM method, aligning NASA NEX-GDDP CMIP6 rainfall projections with observed data (2009–2018) at the four stations. The QDM method preserves relative trends in precipitation extremes while adjusting distributional mismatches, an essential for low-flow accuracy [14]. A Python script automated the QDM method's application by deriving correction factors from the cumulative distribution functions of observed versus modelled data. Ten-year baseline ensured robust calibration, capturing inter-annual variability as validated by Birkinshaw et al. [28] and Piani et al. [29].

3. Results and Discussion

3.1 HEC HMS Calibration and Validation Results

The HEC-HMS model was calibrated (from 01/01/2009 to 31/12/2013) and validated (from 01/01/2014 to 31/12/2018) for Giriulla and Badalgama river gauging stations, and the goodness of fit between the observed and simulated flows was assessed using the objective functions RMSE, NSE, PBIAS, R^2, RSR, and RSR for low flows (90-100% probability of exceedance). Model calibration and validation results at Giriulla and Badalgama are shown in Table 1. According to Moriasi et al. [24], the goodness-of-fit values are within acceptable ranges (either 'good' or 'very good').

The observed and simulated hydrographs for calibration period (Figure 2 and Figure 3) and validation period (Figure 4 and Figure 5) at Giriulla and Badalgama show reasonable agreement, with particularly good alignment during the low-flow conditions. These results confirm the model's capability to replicate basin hydrology, which is especially important for low-flow analysis.

3.2 Flow Duration Curve and Scatter Plot Analysis

Model performance was evaluated using the FDCs and scatter plots, as recommended by Moriasi et al. [24] for continuous daily flow simulations. FDCs, plotted on a logarithmic scale to highlight the low-flow regions (90–100% exceedance), were analysed across peak-flow (0–10% exceedance), intermediate-flow (10–90% exceedance), and low-flow (90–100% exceedance) regimes at both Giriulla and Badalgama stations. As shown in Figure 6 and Figure 7, the model accurately simulated the low-flow region. The FDCs revealed robust alignment between simulated and observed flows in low-flow regions, critical for assessing dry-season water availability.

Scatter plots of the observed and simulated flows showed a particularly good match, with correlation coefficients of 0.82 and 0.88 ($p < 0.01$) for the calibration and validation at Giriulla respectively, and 0.86 and 0.85 ($p < 0.01$) for the calibration and validation at Badalgama, respectively. Simulated flows clustered tightly around the 1:1 line, particularly in the low-flow and intermediate-flow regions, underscoring the model's precision in replicating hydrologic behaviour across the low and intermediate-flow regimes. These findings align with De Silva et al. [11], who demonstrated the superior performance of HEC-HMS in low-flow regions, an aspect critical for water resource planning.

3.3 Projected Future Rainfall Data

Following the correction, the bias-adjusted data significantly improved replication of observed rainfall magnitudes and, consequently, low-flow frequencies, both critical for reliable hydrological projections. For instance, at Aranayake station, under SSP245 (CESM2) scenario, raw NASA NEX-GDDP CMIP6 data underestimated rainfall extremes (Figure 8), while QDM-adjusted outputs closely matched observed rainfall patterns (Figure 9). Low-flow validation confirmed enhanced reliability, with corrected rainfall data aligning within a 5% deviation of observed values, which is critical for accurate dry-season flow simulations. The results underscore the effectiveness of the QDM method in accurately estimating rainfall, which is essential for hydrological modelling, particularly in low-flow regimes. The QDM method's ability to preserve climate change signals while correcting distributional biases ensures that future rainfall projections are both physically consistent and statistically robust. This accuracy substantiates the use of bias-corrected rainfall data as a reliable input for assessing long-term water availability under climate change, particularly in the Maha Oya basin.

3.4 Analysis of the Model Outputs

3.4.1 Future water extraction requirements

The study evaluated future low-flow conditions along the Maha Oya River at 12 critical geographical locations, selected from a total of 9

Table 1 – HEC-HMS model performance at Giriulla and Badalgama river gauging stations

	Giriulla		Badalgama		Performance rating [24]
	Calibration	Validation	Calibration	Validation	
NSE	0.666	0.754	0.729	0.632	Very Good 0.65<NSE≤1.00 Good 0.55<NSE≤0.65
PBIAS	-5.07	-8.51	-4.42	-18.50	Very Good PBIAS≤±15 Good ±15≤PBIAS≤±20
R^2	0.67	0.77	0.74	0.72	Very Good 0.65<R2≤1.00
RSR	0.33	0.25	0.27	0.37	Very Good 0.00<RSR≤0.6
RSR for low flows	0.02	0.03	2.62	0.16	Very Good 0.00<RSR≤0.6

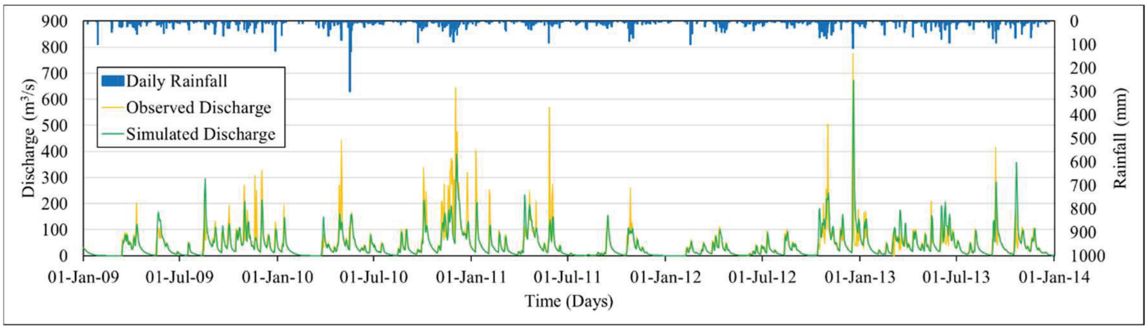

Figure 2 – Simulated flow vs. observed flow hydrograph: Giriulla - Calibration

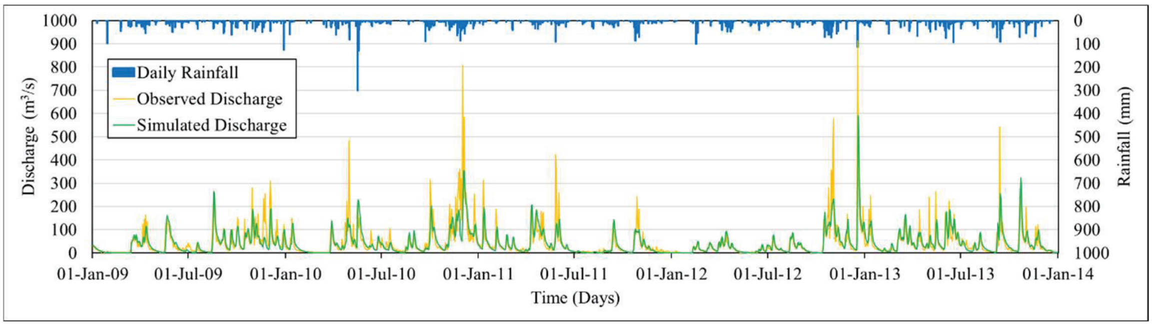

Figure 3 – Simulated flow vs. observed flow hydrograph: Badalgama - Calibration

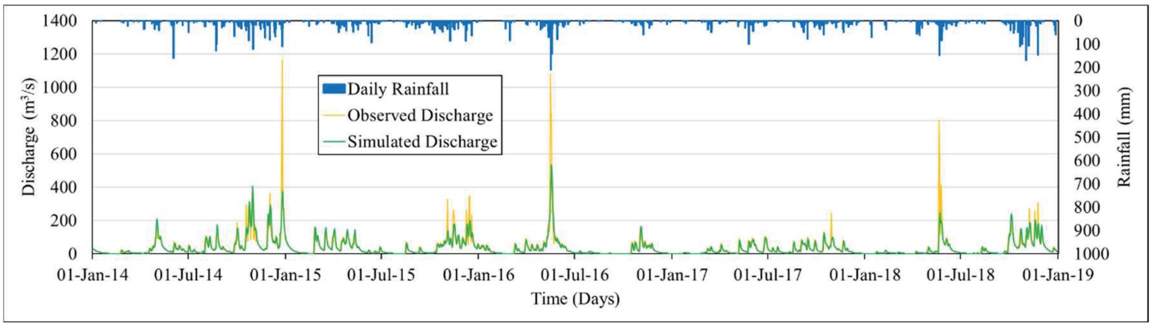

Figure 4 – Simulated flow vs. observed flow hydrograph: Giriulla - Validation

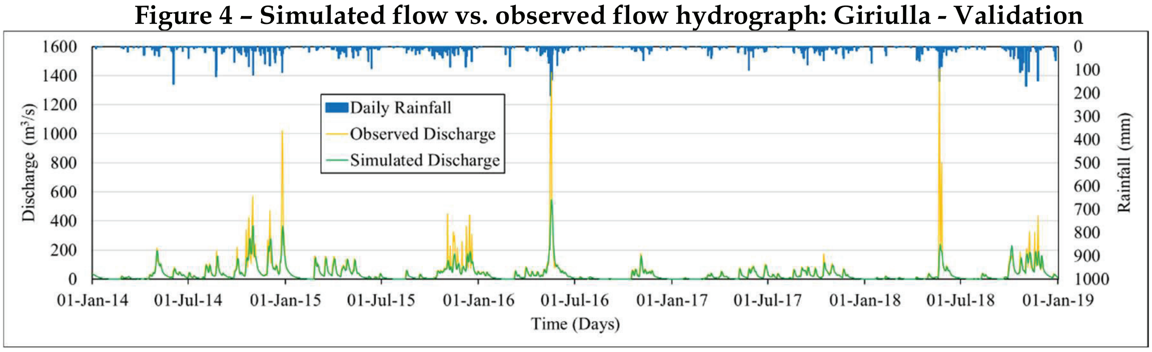

Figure 5 – Simulated flow vs. observed flow hydrograph: Badalgama - Validation

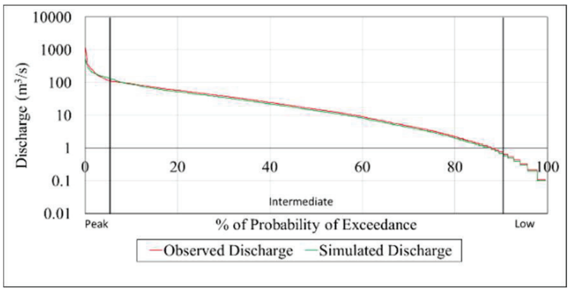

Figure 6 – FDC for Giriulla - Validation

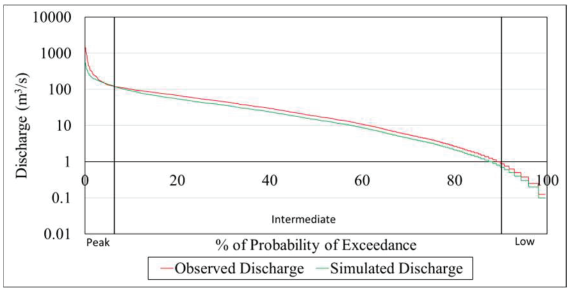

Figure 7 – FDC for Badalgama - Validation

existing and 8 proposed potable water extraction points [7] managed by the NWSDB. These points span three administrative regions [Northwestern, Western North, and Sabaragamuwa Regional Support Centres (RSCs)] and play a critical role in addressing the growing demand for potable water. As of 2021, daily extraction totalled 46,805 m³ (17.08 MCM/year), with projections indicating a sixfold increase to 333,230 m³/day (121.63 MCM /year) by 2040 (Table 2), driven by urbanization and a population rise to 4.3 million [8].

This expansion necessitates large-scale infrastructure development, including water treatment plants and capacity upgrades, to manage the 286,425 m³/day increase in extraction. This growth reflects the basin's transition from rural to urban water supply dominance [7]. Such projections underscore the urgency of reconciling resource exploitation with ecological sustainability, particularly in drought-prone reaches vulnerable to low-flow stress.

3.4.2 Future low-flow condition

Future low-flows (90–100% exceedance) in the Maha Oya basin are projected to decline by up to 90–100% under all climate models (HadGEM3-GC31-LL, CESM2, and ensemble) for both SSP245 and SSP585 (Table 3). SSP245 simulations stated in Table 4 revealed spatially heterogeneous low-flow reductions: downstream stations (e.g., Pannala, Giriulla) exhibited gradual declines (88–95%) from near-future to far-future periods, while upstream locations (e.g., Alawwa, Karadana) showed mid-future intensification (95–96%) followed by partial recovery. Notably, Mawanella-Kappagoda and Hemmathagama faced persistent zero low-flows across all scenarios, signalling acute water scarcity risks [30].

Under SSP585 (Table 5), intensified radiative forcing (~7.0 W/m² by 2100) amplified the low-flow reductions. HadGEM3-GC31-LL projected near-future decline in low-flows of 33–35%, escalating to 90% by 2100. CESM2 simulations indicated near-total loss of low-flows (100% reduction) by mid-century, with the ensemble predicting 85–100% reductions. Upstream regions (e.g., Hiriwadunna) experienced zero flows under CESM2 and ensemble projections, reflecting climate-driven hydrological collapse [31].

Intensified warming and erratic rainfall under SSP585 exacerbated basin-wide aridity, with low-flows averaging 80% lower than those projected under SSP245 [32]. These low-flow trends aligned with global projections of increased drought frequency under high-emission pathways [33]. The divergence between the models, CESM2's extreme drying versus HadGEM3's phased decline, highlighted uncertainties in regional hydro-climate responses. However, consensus on severe reductions underscored the urgency of adaptive measures, including demand management and infrastructure resilience, to mitigate water insecurity.

3.4.3 Low-flows vs. future water extractions

Climate and hydrological models projected significantly reduced dry-season flows in the Maha Oya Basin, with Mawanella, Hemmathagama, and Hiriwadunna facing persistent near-zero low-flows under future climate scenarios [34], [35]. This jeopardizes three major planned future water extractions at Rambukkana (22,000 m³/day), Mawanella (19,800 m³/day), and Hemmathagama (24,200 m³/day), which collectively aim to extract 66,000 m³/day. These demands starkly contrast with the projected hydrological deficits, posing a serious risk of supply shortfalls during critical dry periods.

Over-extraction of surface water and groundwater for agriculture, sand mining, and urban use has exceeded recharge rates, depleting the base flows that are critical during dry periods in the Maha Oya. Groundwater

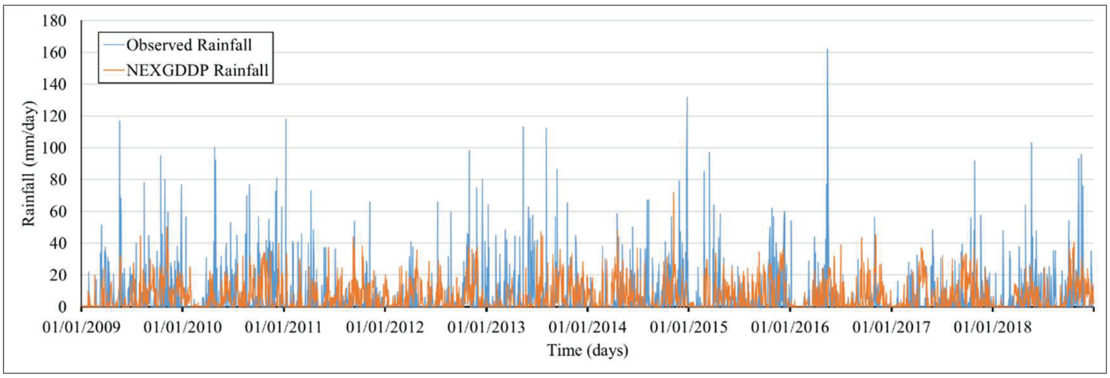

Figure 8 – Observed vs. NASA NEX-GDDP CMIP6 rainfall (CESM2 under SSP245) at Aranayake (2009-2018)

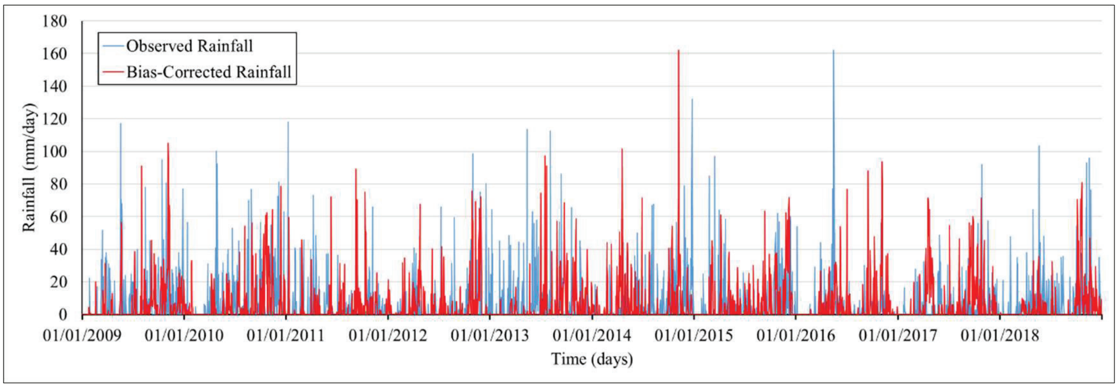

Figure 9 – Observed vs. bias-corrected rainfall (CESM2 under SSP245) at Aranayake (2009-2018)

Table 2 – NWSDB existing and future water extractions

Regional Support Centre (RSC) / NWSDB administration boundary	Water extraction point location and coordinates	Geographical location	Existing extraction @2021 (m^3/day)	Total future extraction @2040 (m^3/day)
Northwestern	Pannala (7°19'N, 80°01'E)	1	550	66,000
Western North	Kotadeniyawa (7°17'N, 80°04'E)	2	-	22,000
Western North	Kotadeniyawa (7°17'N, 80°04'E)	2	1,375	4,000
Western North	Kotadeniyawa (7°17'N, 80°04'E)	2	-	22,000
Northwestern	Giriulla (7°19'N, 80°08'E)	3	4,950	24,200
Western North	Madurupitiya (7°17'N, 80°09'E)	4	1,980	1,980
Western North	Kamarangoda (7°14'N, 80°10'E)	5	-	22,000
Western North	Kamarangoda (7°14'N, 80°10'E)	5	-	22,000
Sabaragamuwa	Warakapola – Thihariya (7°17'N, 80°14'E)	6	-	22,000
Northwestern	Alawwa (7°17'N, 80°15'E)	7	1,100	1,100
Sabaragamuwa	Galigamuwa - Helamada (7°19'N, 80°18'E)	8	9,900	9,900
Northwestern	Karadana (7°19'N, 80°18'E)	9	-	31,900
Northwestern	Karadana (7°19'N, 80°18'E)	9	-	6,050
Sabaragamuwa	Hiriwadunna (7°17'N, 80°23'E)	10	9,350	12,100
Sabaragamuwa	Rambukkana - Hiriwadunna (7°17'N, 80°23'E)	10	-	22,000
Sabaragamuwa	Mawanella – Kappagoda (7°14'N, 80°26'E)	11	16,500	19,800
Sabaragamuwa	Hemmathagama (7°08'N, 80°28'E)	12	1,100	24,200
			46,805	333,230

Table 3 – Average percentage change of low-flows for all climate models under the SSP245 and SSP585 scenarios

Location	Intake reference	Average percentage change of low flows (%)			
		NF average	MF average	FF average	Overall average
Pannala	1	-88.59	-89.29	-95.03	-90.97
Kotadeniyawa	2,3,4	-88.57	-89.24	-94.97	-90.93
Giriulla	5	-88.66	-89.31	-95.02	-91.00
Madurupitiya	6	-88.74	-89.35	-95.06	-91.05
Kamarangoda	7, 8	-88.76	-89.31	-95.07	-91.04
Warakapola – Thihariya	9	-88.66	-89.34	-95.16	-91.06
Alawwa	10	-90.02	-89.54	-95.89	-91.82
Galigamuwa - Helamada	11	-90.09	-89.58	-96.02	-91.90
Karadana	12, 13	-90.10	-89.46	-96.05	-91.87
Hiriwadunna	14	-100.00	-99.52	-100.00	-99.84
Rambukkana - Hiriwadunna	15				
Mawanella – Kappagoda	16	Zero Low-Flow	Zero Low-Flow	Zero Low-Flow	Zero Low-Flow
Hemmathagama	17	Zero Low-Flow	Zero Low-Flow	Zero Low-Flow	Zero Low-Flow

tables in Mawanella and Hemmathagama have declined by 30% over two decades, primarily due to unsustainable irrigation and sand mining [3], [4]. According to IPCC [30], climate change intensified these pressures, with reduced rainfall reliability and increased drought frequency under potential future climate scenarios. Land-use shifts, notably 23% deforestation and 18% expansion of impervious surfaces since 2000, have further reduced infiltration, diminishing groundwater recharge and dry season flows in the Maha Oya [5].

Persistent low flows pose a threat to aquatic ecosystems that rely on stable flow regimes [36] and compromise water access for basin residents. To address competing demands, integrated strategies are imperative: managed aquifer recharge, rainwater harvesting, and reforestation could enhance storage and infiltration [37]. Thus, regulatory measures, including sustainable extraction quotas aligned with ecological thresholds, sand mining restrictions, and adaptive strategies such as managed aquifer recharge, are essential to reconcile water supply ambitions with the Maha Oya basin's hydrological limits.

4. Conclusions, Limitations, and Future Research

HEC-HMS hydrological model was applied to evaluate future low-flow dynamics in the Maha Oya River basin under climate change scenarios, focusing on potable water availability across 12 critical intake locations. Simulations encompassed three future time periods (near-future, mid-future, and far-future), incorporating NASA NEX-GDDP CMIP6 precipitation data with three climate modelling approaches (HadGEM3-GC31-LL, CESM2, and ensemble) under two socio-economic pathways (SSP245 and SSP585). The study underscored the significant vulnerability of the Maha Oya River basin to the impacts of climate change, with severe reductions in the low flow conditions projected under both scenarios. Results revealed a progressive decline in low-flows, with a 90% reduction projected by the late 21st century, becoming particularly severe during the far-future period (2075–2099). Critically, Mawanella - Kappagoda and Hemmathagama exhibited near-zero average low-flows across all scenarios.

These conditions pose a significant threat to the planned future potable water extractions, particularly at Rambukkana, Mawanella, and Hemmathagama, requiring urgent action to ensure a sustainable water supply in the face of increasing demand.

The projected decline in low flows could significantly impair water supply reliability, especially during dry seasons when demand peaks. Policymakers must consider adaptive strategies such as demand-side management, investment in alternative water sources (e.g., groundwater or rainwater harvesting), and flexible infrastructure planning to mitigate supply-demand imbalances. Early integration of climate-resilient water policies will be essential

Table 4 – Average low-flows under the SSP245 scenario

Location	Intake	NF	MF	FF	NF	MF	FF	NF	MF	FF
		HadGEM3-GC31-LL			CESM2			Ensemble		
Pannala	1	4,266.57	8,706.24	5,384.62	740.35	0.00	0.00	7,685.94	2,394.22	1,059.89
Kotadeniyawa	2, 3, 4	4,106.29	8,545.37	5,318.38	709.82	0.00	0.00	7,510.39	2,299.58	1,022.04
Giriulla	5	3,961.27	8,327.71	5,185.89	633.50	0.00	0.00	7,327.21	2,280.66	974.72
Madurupitiya	6	3,823.89	8,147.91	5,091.26	557.17	0.00	0.00	7,113.50	2,186.02	889.55
Kamarangoda	7, 8	3,762.83	8,081.66	5,053.41	496.11	0.00	0.00	7,021.91	2,167.10	861.16
Warakapola - Thihariya	9	3,617.81	7,892.40	4,892.53	427.42	0.00	0.00	6,982.16	2,081.93	804.38
Alawwa	10	3,098.80	6,851.43	4,277.42	106.86	0.00	0.00	5,129.05	1,561.45	141.95
Galigamuwa - Helamada	11	3,098.80	6,728.41	4,182.78	61.06	0.00	0.00	4,984.03	1,533.06	75.71
Karadana	12, 13	3,098.80	6,624.32	4,135.47	30.53	0.00	0.00	4,831.38	1,514.13	9.46
Hiriwadunna	14	0.00	113.56	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rambukkana - Hiriwadunna	15									
Mawanella - Kappagoda	16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hemmathagama	17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 5 – Average low-flows under SSP585 scenario

Location	Intake	NF	MF	FF	NF	MF	FF	NF	MF	FF
		HadGEM3-GC31-LL			CESM2			Ensemble		
Pannala	1	2,694.28	4,334.19	861.16	0.00	0.00	0.00	1,381.48	312.29	0.00
Kotadeniyawa	2,3,4	2,633.22	4,220.64	823.31	0.00	0.00	0.00	1,305.16	246.05	0.00
Giriulla	5	2,564.52	4,088.15	747.60	0.00	0.00	0.00	1,251.73	141.95	0.00
Madurupitiya	6	2,518.73	3,917.81	662.43	0.00	0.00	0.00	1,129.61	75.71	0.00
Kamarangoda	7,8	2,503.46	3,870.49	605.65	0.00	0.00	0.00	1,083.82	18.93	0.00
Warakapola - Thihariya	9	2,465.30	3,709.62	511.02	0.00	0.00	0.00	1,060.92	0.00	0.00
Alawwa	10	2,160.00	3,274.30	170.34	0.00	0.00	0.00	656.40	0.00	0.00
Galigamuwa - Helamada	11	2,144.73	3,226.99	123.02	0.00	0.00	0.00	633.50	0.00	0.00
Karadana	12,13	2,114.20	3,208.06	104.10	0.00	0.00	0.00	587.70	0.00	0.00
Hiriwadunna	14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rambukkana - Hiriwadunna	15									
Mawanella - Kappagoda	16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hemmathagama	17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

for safeguarding domestic water security in the region.

Key limitations of the study include the restriction of the analysis to two SSPs, which constrains the ability to assess lower-emission mitigation scenarios, and the exclusion of the impact assessment of compound extreme events (e.g., droughts coupled with heat waves) on potable water availability, which could exacerbate vulnerabilities.

To support the reliability of future low-flow projections, additional model validation was performed focusing specifically on the low-flow regime. The RSR for flows exceeding the 90^{th} percentile was used as a metric, confirming acceptable model performance during dry periods. Furthermore, ensemble averaging and QDM bias correction were applied to reduce uncertainties in GCM outputs, although structural model assumptions and exclusion of groundwater interactions may still affect confidence in projections.

By providing a framework for assessing climate-induced stress on potable water, this study contributes to the development of a methodology that can be applied to other tropical catchments facing similar challenges. Future research should prioritise integrated hydrological modelling that explicitly couple surface water and groundwater interactions to refine water balance estimations, especially in areas experiencing significant over-extraction.

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