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Assessing the Compound Impacts of Climate Change and Land Use Dynamics on Future Groundwater Availability in Dry Land Areas of Sri Lanka

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Abstract. Climate change and land use and land cover (LULC) change are the primary challenges that disrupt groundwater availability. While numerous studies have examined their individual impacts, a critical gap exists in understanding their combined impact on groundwater availability. To address this gap, the present study assesses the compound impacts of climate change and LULC change in the Kumbukkan Oya catchment, a dryland area in southeastern Sri Lanka. The analysis uses hydrometeorological data, groundwater levels, borehole logs, and catchment characteristics such as land use, soil type, and elevation. Climate data were obtained from 1989 to 2011, while the groundwater level data and hydrological data were used from 2022 to 2024 at a mostly daily time step. Groundwater flow was then numerically modeled with MODFLOW. Projected future climate was obtained from the CNRM-CM6-1-HR General Circulation Model (GCM) and downscaled to the local scale using a stochastic Random Forest (RF) machine learning algorithm. Land-use data of 2018 and projected for future conditions were employed in assessing LULC dynamics. According to the result, the model captures the seasonal patterns of decline and recovery, particularly in the upstream, although some overestimation occurred in mid-catchment areas. Future projections indicate a decrease in seasonal rainfall compared to the baseline period, with reduced average rainfall but still frequent extreme events. The future period total rainfall will be 1,552 mm, and the observed total of 1,733 mm. Based on the projected results, groundwater levels are expected to decline by approximately 0.43 m to 0.65 m compared to observed conditions. Therefore, simulation reveals that the Kumbukkan Oya catchment has some extent of resilience in the groundwater level relative to the projected climate and land use change. However, localized tendencies in the fall in groundwater levels suggest the need for site-specific adaptation responses, particularly over vulnerable recharge zones.

Keywords: Climatic alterations, Compound Impacts, Land use changes.

1 Introduction

Groundwater is one of the most important natural resources on Earth, offering several advantages over surface water, such as better quality, lower risk of contamination, and more stable availability throughout the year. Groundwater is essential for global water needs, especially agriculture, which uses 69%. In Asia, 76% of groundwater supports irrigation, underscoring its role in food security. Additionally, groundwater supports domestic and industrial uses and helps sustain ecosystems, making it essential for both human and environmental well-being [1].

Groundwater depletion is a growing global concern, with many regions experiencing sharp declines in groundwater levels (GWLs), evident from well data and Gravity Recovery and Climate Experiment (GRACE) satellite observations [2]. However, this use is not evenly distributed—nearly two-thirds was withdrawn in Asia, particularly in South and East Asia, where dependence on groundwater is especially high [1].

Groundwater depletion is primarily caused by climate change and land use changes[3,4]. Land Use and Land Cover (LULC) changes, such as deforestation or urbanization, affect land surface characteristics, which in turn impact infiltration and runoff. Meanwhile, climatic variations, including shifts in precipitation and temperature, directly influence groundwater recharge. Understanding climate change along with incremental LULC changes is synergistic, as these factors operate in complex interdependent ways. Therefore, studying the combined consequences of these factors on groundwater availability is more rational than assessing the impacts one at a time [5].

While several studies have examined the compound effects of climate change and LULC change on surface water [6,7], relatively few investigations have critically examined their effects on groundwater [4,5]. This gap highlighted the need to investigate the compound impacts of climate change and LULC change on the availability of groundwater. Additionally, this assessment is crucial in the development of long-term water management practices that contribute to mitigating the effects of drought by providing a constant groundwater supply.

As indicated by the latest assessment report from the Intergovernmental Panel on Climate Change (IPCC), Assessment Report [8], South Asia is one of the hotspots in the world for climate-induced hazards. Within this context, Sri Lanka, particularly its dry zone, is increasingly vulnerable. This region has experienced a significant reduction in rainfall and heightened rainfall seasonality, impacting groundwater recharge. Since over 60% of Sri Lanka's population depends on agriculture, mainly in the dry zone, groundwater remains a vital resource for sustaining livelihoods. However, the Water Resources Board (WRB) data in 2017 show that much of the dry zone has low groundwater yields

(0–50 lpm), underscoring the scarcity and vulnerability of water resources in these areas [9]. Also, to date, no studies in Sri Lanka have assessed the compound impacts of climate change and land use dynamics on groundwater using Coupled Model Intercomparison Project (CMIP) 6 data.

Therefore, this study focuses on the Kumbukkan Oya catchment to investigate the compounded impacts of climate change and LULC changes on groundwater resources in Sri Lanka's dry zone. The main objective of this study is to evaluate the effects of climate change and potential LULC changes on groundwater aquifers using an integrated approach. This involves combining a process-based physical model with machine learning (ML) techniques to simulate and predict groundwater responses under different future scenarios.

2 Study Materials

a. Study Area

Kumbukkan Oya catchment, which is shown in **Fig.** is in Sri Lanka’s Uva and Eastern provinces, with most of it located in the Monaragala District. Covering 1,227 km², the catchment has an elevation range from the mean sea level to 1,400 m above sea level. The Kumbukkan Oya River flows for 116 km, supporting the largest irrigation system in Monaragala. Located at approximately 6.8°N and 81.5°E, the catchment is essential for agriculture and water resources in the region. It irrigates about 2,000 acres of cultivated land and plays a vital role in agriculture and water management in the areas surrounding it [10].

Borehole data reveal a layered subsurface of topsoil, sand, clay, gravel, weathered rock, and bedrock. The catchment receives an average annual rainfall of about 1,700 mm, with distinct seasonal patterns: the Northeast Monsoon (35.2%) and Second Inter-Monsoon (21.3%) contribute the highest rainfall, while dry spells prevail mid-year. The region experiences an average annual temperature of 23°C and a pan evaporation of approximately 1,100 mm, both key factors affecting the hydrological balance. GWLs mostly range from 80 to 400 m, with higher values at elevated terrain, influenced by topography and aquifer properties.

According to the 2018 land use map, forest land is the dominant class in the catchment, covering 62% of the area. Agricultural land accounts for 26%, underscoring the catchment’s critical role in supporting local farming. Built-up areas comprise 6%, indicating limited urban development. The remaining land consists of rocky terrain (4%), water bodies (1%), and a small portion (0.8%) classified as wetlands, bare lands, and sandy areas.

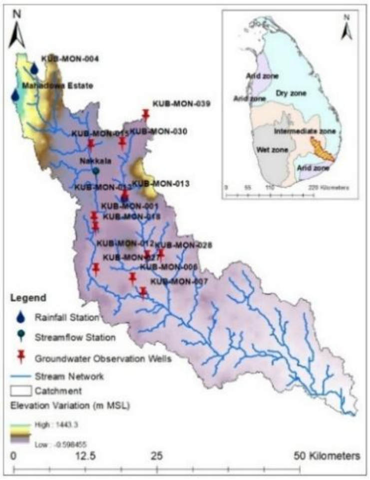

Fig. 1. Kumbukkan Oya catchment and the locations of the rainfall, streamflow, and groundwater monitoring stations

b. Data Collection

Various datasets were collected from both national and global sources. A 30 m × 30 m resolution Digital Elevation Model (DEM) was obtained from the Shuttle Radar Topography Mission (SRTM). GWLs and borehole data from 2022 to 2024 were collected from the WRB. Daily rainfall data for the periods 1989–2011 and 2022–2024 were obtained from the Department of Meteorology and the WRB. Daily streamflow data (2020–2024) were sourced from the Irrigation Department. Temperature data for the same periods were acquired from the Department of Meteorology and NASA POWER (https://power.larc.nasa.gov/data-access-viewer/). Pan evaporation data (monthly) for 2019/2020 were taken from the Hydrological Annual published by the Ministry of Irrigation. 2018 land use data (scale 1:100,000) were collected from the Survey Department. Climate data from Global Climate Models (GCMs) for 1989–2011 and 2030–2049 were sourced from the IPCC data portal (https://www.ipcc-data.org/).

3 Methodology

The groundwater model was developed using MODFLOW to simulate the aquifer response [11,12]. Parameter optimization was carried out by optimizing hydraulic properties to match observed GWLs. To assess future groundwater responses to climate variability, climate projections were introduced from the CNRM-CM6-1-HR model, a high-resolution GCM under the CMIP6 framework [13]. This model was selected for its demonstrated capability in accurately representing South Asian monsoonal rainfall and its fine spatial resolution (0.5° × 0.5°), making it suitable for small island nations like Sri Lanka [14]. The SSP5-8.5 scenario was employed to simulate potential future extremes. Climate data for the baseline period (1989–2011) and the future projection period (2030–2049) were used for comparison and scenario analysis.

a. Development of the Groundwater Flow Model

A groundwater flow model was developed for a 1,227 km² area using MODFLOW, incorporating lithology, GWLs, and recharge data. The model domain was discretized into a single-layer finite difference grid with 266 columns, 280 rows, and a cell size of 250 m. The DEM was used to define the model top. Boundary conditions included a constant head of 0 m at the coastal boundary to represent mean sea level, and a time-varying constant head at the upstream boundary based on GWL observations from nearby monitoring wells during the simulation period. No-flow boundaries were assigned to the eastern and western sides. Recharge was applied using a recharge-to-rainfall ratio of 0.22, with daily rainfall data used to generate time-series recharge inputs across the model domain. Initial heads for the transient simulation were taken from steady-state results, and the model was run using daily time steps over 164 stress periods from 1 July to 12 December 2023.

b. Development of the ML Model for Climate Data Downscaling

Due to the coarse resolution of GCMs, statistical downscaling is preferred over dynamic methods for its computational efficiency and ability to apply bias correction. Among statistical techniques, ML methods like Random Forest (RF) are most effective due to their robustness, ability to model non-linear relationships, and minimal preprocessing needs [15]. Therefore, RF was chosen for downscaling GCM precipitation data in this study.

The downscaling process involved preparing both observed and GCM-predicted precipitation datasets, where input variables included the GCM-derived precipitation along with time-related attributes such as year, month, and day. The target variable was the observed precipitation, representing the actual measured values. Both datasets were merged by date, and temporal features were extracted to enhance model performance. The combined dataset was then split into training and testing sets using an 80/20 ratio, with 80% allocated for training and 20% for testing. An RF model was trained using 100 trees to ensure robust performance while maintaining computational efficiency. The trained model was later applied to correct the future GCM projections, ensuring improved accuracy for climate impact assessments.

4 Results and Discussion

a. Results and Analysis of Transient Groundwater Flow Simulation

The transient groundwater flow model simulated the seasonal fluctuation from June 2023 to January 2024. The declining trend in GWLs from June to October and the increasing trend during October to January followed a uniform pattern in all the wells. **Fig.** shows the hydrograph in well KUB_MON_004 from the upstream area. The model accurately captures both the declining and recovery phases, with some slight overestimation of peak, and the residual of nearly -0.8 m.

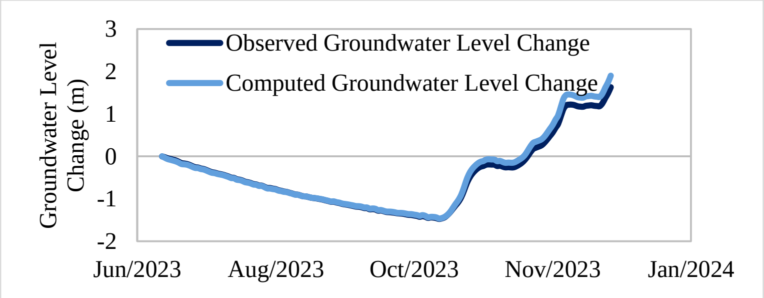

Fig. 2. GWL Change at the monitoring well KUB_MON_004 (Upstream) throughout the transient simulation period

The mid-catchment well KUB_MON_015 (**Fig.**), however, exhibited systematic overestimation of GWLs with the residual of -1.0 m. Overall, the model reproduced seasonal dynamics at upstream wells quite well, while mid-catchment performance could be enhanced. The results indicate that the model is well calibrated for general trend and seasonal variation prediction, but further refinement may be needed to distinguish site-specific recharge and flow processes.

These types of disparities between the computed and observed GWLs appear because of the site-specific conditions. Among the likely causes are groundwater pumping, which was not accounted for because the data were limited. The annual amount of groundwater abstraction of the Monaragala District is estimated to be 4000 m^3/day [16], excluding the extraction from the private individual wells. If the drawdown is calculated using a model cell size of 250 m x 250 m and assuming an assigned specific yield value of 0.1 for sandy soil, the estimated drawdown would be approximately 0.7 m/day. This rate of abstraction is also consistent with the disparity reported between computed and observed groundwater heads in the downstream region. Therefore, incorporation of this abstraction in the model could significantly reduce the disparity and improve computed GWL precision.

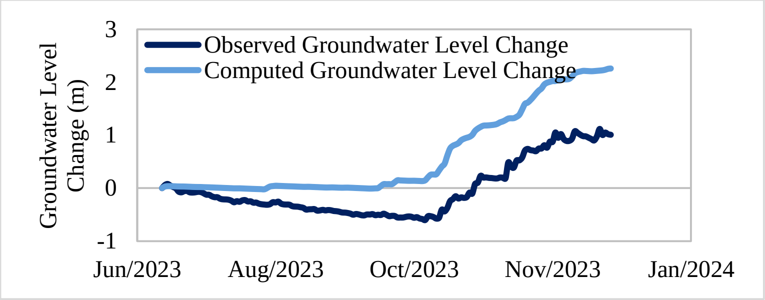

Fig. 3. GWL change at the monitoring well KUB_MON_015 (midstream) throughout the transient simulation period

Also, this overestimation can be attributed to the impact of nearby land cover categories. In agricultural areas such as those around KUB-MON-015, large abstraction of groundwater for irrigation can reduce actual water levels. If such land–use–specific pumping effects are not adequately simulated by the model, it may cause computed GWLs that are higher than the true field observed levels. In the model, the entire catchment is considered as a single recharge zone. Except for the upstream and downstream parts, no-flow boundaries have been given to the other two sides. But additional complexity can be introduced in the middle of the catchment due to the change in land use and varying recharge rates. Additionally, the influence of lateral outflows and inflows cannot be efficiently modeled, supporting further overestimation of GWLs.

Moreover, model assumptions and simplifications can also be the cause of these deviations. For example, MODFLOW assumes that aquifer properties, including hydraulic conductivity and storativity, are homogeneous. Aquifers in the real world are usually heterogeneous, and ignoring local variations in properties can lead to incorrect simulations. Also, boundary conditions such as no-flow boundaries may not be representative of actual conditions, especially when there are lateral inflows or outflows, which are not accounted for by the model. These assumptions might cause the model to overpredict GWLs.

b. Results of Downscaled Climate Projections and Precipitation Pattern Analysis

Due to limited data, the precipitation from both GCM and the single observation point was compared over time. **Table** shows the long-term average monthly rainfall variation during a monsoon cycle. According to the data in the table, there is a clear declining pattern of seasonal rainfall during all phases of the monsoon. A closer examination of the monsoon-specific trends suggests that the Second Inter-Monsoon (October-November) and Southwest Monsoon (May-September) periods, which used to get the maximum rainfall in the past, will experience a significant decline in the future. By comparison, the Northeast Monsoon (December-January) and First Inter-Monsoon (March–April) phases, which are historically lower rains, also experience a slight reduction in future rain, following the trend of becoming progressively drier across all the seasons.

Table 1. Long-term monthly average rainfall data during a monsoon cycle

Long-Term Average Monthly Precipitation (mm) [Based on the data from 1989 to 2011]			Long-Term Average Monthly Future Precipitation (mm) [Based on the data from 2030 to 2049]
Month	Observed	GCM	GCM
October	277.4	299.1	255.5
November	271.6	276.5	228.1
December	229.1	238.2	144.7
January	114.1	116.3	89.7
February	115.4	117.8	114.4
March	90.6	94.6	99.3
April	133.3	141.6	121.1
May	130.1	141.6	146.1
June	51.6	57.9	50.4
July	65.2	69.7	41.7
August	96.0	99.1	100.5
September	147.9	156.7	160.1

c. Compound Impacts Assessment

This section aims to assess the compound impacts of climate change and potential LULC changes on fluctuations in GWLs. Following the United Nations Population Division's

World Urbanization Prospects, World Bank staff estimates have projected a steady increase in the rural population from 1960 to 2023 [17]. Additionally, according to a study by Dey et al. (2024) [18], the population of Sri Lanka is projected to increase between 2030 and 2060, based on the logistic growth model. As the population grows, pressure on food production, shelter, and infrastructure is likely to mount, particularly in developing regions such as the Monaragala District. This will result in the conversion of forests to agricultural land and built-up areas. Therefore, assessment assumes that, in the future, population growth will drive land use transformations characterized by a reduction in forest cover, an expansion of agricultural land, and an increase in built-up areas. Incorporating these transformations within the groundwater model, the analysis accounts for the interactive influence of both drivers, giving an integrated picture of their potential influences on groundwater resources.

GWL fluctuation estimation under the compound impacts of climate change and LULC change indicates a generally moderate hydrological response in the catchment. Despite the reduction in all the phases of rainfall in the seasons and extensive land transformation, the varying GWLs were nearly within a narrow range. Overall, the mean average GWL decreased by approximately 0.65 m and the maximum GWL by approximately 0.43 m across the catchment. These reductions are hydrologically consistent with decreased infiltration caused by increased impervious surfaces and loss of vegetation cover, and greater groundwater pumping for irrigation. Lower monsoonal rains also contribute to the decreased opportunity for recharge, further diminishing the demand on groundwater resources.

5 Conclusions and Recommendations

a. Conclusion

This study was carried out to analyze how climate change-induced LULC changes can affect groundwater availability in the arid zone of Sri Lanka, namely the Kumbukkan Oya catchment. To achieve this, the study aimed to develop a numerical groundwater flow model using MODFLOW and apply ML techniques to downscale climate projections to the local scale.

Generally, on all observation wells, there was a decrease in GWL between June and October 2023, followed by a sharp rise up to January 2024. Overall, the model performed well in upstream areas; its lower accuracy in midstream regions highlights the need for localized parameter refinement, better treatment of recharge uncertainty, and enhanced calibration using additional field data. The total annual rainfall during the baseline period

(1989-2011) was approximately 1,733 mm, while projections for 2030-2049 show a decrease to about 1,552 mm. This is important to groundwater recharge, surface water supply, and agriculture planning within the catchment.

However, the compound impact assessment of climate change and LULC change shows an average GWL decline, suggesting that the catchment is sufficiently resilient to these compound stressors. This may be because there are deeper aquifers, larger storage capacity in the aquifers, and spatially heterogeneous areas of recharge that buffer the effects of declining rainfall and increasing land use intensity. Additionally, the low degree of change is an indicator that the system can still be below critical groundwater stress levels. However, while aquifer response has so far been steady, accelerating land use intensification and long-term climate variability can push the system beyond its buffering capacity.

Results of this study benefit the efficient management of Sri Lanka's dry zone groundwater resources, in the case of the Kumbukkan Oya catchment. The study provides a scientific basis for better planning and water allocation. An understanding of how GWLs can reduce, especially during droughts, empowers governments to formulate effective water use plans, allocate priority uses such as drinking and irrigation, and implement recharge enhancement practices such as artificial recharge and soil conservation. Moreover, an understanding of how deforestation and urbanization affect groundwater recharge guides land use zoning and policy guidelines. These results also justify the construction of early warning systems by establishing thresholds for initiating water conservation actions at key times.

b. Recommendations

To improve the enhancement of future studies, it is necessary to address the shortcomings of this study. These are mainly data deficiencies, simplifications in model assumptions, and environmental and human influences are not accounted. The following are suggested to reduce such limitations and enhance the performance of future groundwater models.

- Future research should include the effects of socio-economic factors, e.g., population growth and land demand, on groundwater use.
- It is recommended to investigate the use of coupled climate-hydrology-socioeconomic models for more integrated impact analysis.
- More comprehensive soil and geology information in models can be utilized to refine model accuracy, especially in mid-catchment regions.
- Also, the use of multiple GCMs and several SSP scenarios can be recommended.

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