INTEGRATING REMOTE SENSING AND HYBRID MACHINE LEARNING FOR DEVELOPING A GRIDDED GROUNDWATER STORAGE DATASET FOR DIFFERENT CLIMATE SCENARIOS IN SRI LANKA

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Degree of Master of Engineering in
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-- 11/03/2026

Dr B. C. Dissanayake — Date

ABSTRACT

Integrating Remote Sensing and Hybrid Machine Learning for Developing a Gridded Groundwater Storage Dataset for Different Climate Scenarios in Sri Lanka

Reliable groundwater monitoring is essential to ensure water security. Yet, many regions lack dense observational networks. High-resolution gridded groundwater datasets therefore provide valuable alternatives for characterising groundwater dynamics. The Gravity Recovery and Climate Experiment (GRACE) offers large-scale terrestrial water storage anomaly (TWSA) data, but its coarse spatial resolution limits regional applicability. Recent studies have increasingly utilized machine learning (ML) to improve GRACE-based groundwater estimates; however, most have relied on individual ML models, which enhance prediction accuracy only to a limited extent. Based on these grounds, this study proposes a stacking ensemble machine learning (SEML) framework that integrates Random Forest (RF), eXtreme Gradient Boosting (XGBoost), Light Gradient Boosting Machine (LightGBM), and Categorical Boosting (CatBoost) for more precise statistical downscaling of GRACE-derived groundwater storage anomalies (GWSA) to finer spatial resolutions. The framework was first evaluated in the Kumbukkan Oya Basin, where GWSA was downscaled from 0.25° to 0.05° resolution, achieving strong predictive skill (R^2 = 0.84, RMSE = 3.04 cm), with grid-wise validation against GRACE yielding R^2 values exceeding 0.9 and in-situ groundwater level comparisons showing correlations above 0.7 in most wells. To further assess the physical consistency of the downscaled signals, an independent Physics-Informed Neural Network (PINN) framework was developed for the same basin. The groundwater system was idealised as a one-dimensional transient unconfined flow, reflecting the predominantly linear basin geometry. The PINN model embedded the Boussinesq groundwater flow equation directly into the learning process and was trained using rainfall as the primary forcing, with the uppermost and lowermost wells prescribed as transient boundary conditions and two interior wells used for training and testing. The model reproduced historical groundwater dynamics with a correlation coefficient of 0.81 and an RMSE of 0.57 m at the testing interior well, providing physics-based validation of the downscaled GWSA patterns. The methodology was subsequently extended to the entire Sri Lankan domain, generating the first high-resolution national GWSA dataset capable of resolving spatial heterogeneity and groundwater stress patterns. Future groundwater dynamics were assessed using precipitation projections from the CMIP6 CNRM-CM6-1 model under SSP2-4.5 and SSP5-8.5 scenarios for near- (2021–2039) and mid-century (2040–2059) periods. Trend analysis revealed spatially coherent groundwater depletion hotspots, particularly across the dry and intermediate zones, with projected GWSA declines locally exceeding −1.5 cm yr^{-1} under high-emission conditions. By integrating ensemble learning, climate projections, and national-scale analysis, this study delivers a robust, transferable framework for groundwater monitoring, climate impact assessment, and evidence-based groundwater management in data-limited regions.

Keywords: climate scenarios, GRACE/GWSA, groundwater monitoring, Kumbukkan oya, PINN, remote sensing in hydrology, statistical downscaling

DEDICATION

This thesis is dedicated to all those who provided unwavering support and encouragement throughout my academic journey. It stands not only as a scholarly contribution but also as a testament to perseverance during one of the most challenging periods of my life, reflecting the guidance and compassion of those who stood by me throughout this endeavour.

I express my sincere gratitude to my supervisor, Dr. Chatura Dissanayake, whose insightful guidance, constant encouragement, and generous mentorship were instrumental in shaping this research. I also respectfully dedicate this work to Dr. Luminda Gunawardhana and Prof. Lalith Rajapakse, whose exceptional subject knowledge, thoughtful guidance, and humanistic approach greatly enriched both this study and my academic growth.

This thesis is lovingly dedicated to my family for their continuous encouragement and unconditional support. In particular, I dedicate this work to my parents, whose patience, sacrifices, and belief in my abilities enabled me to pursue and fulfil an important academic aspiration that has long been close to their hearts.

I further dedicate this thesis to my friends and research colleagues for their motivation, support, and positivity throughout this journey. Finally, this work is dedicated to all those who are passionate about research, to those who courageously pursue academic advancement despite challenges, and to everyone who supported me in becoming independent in both my academic pursuits and personal life.

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TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ANN	Artificial Neural Network
CC	Pearson Correlation Coefficient
CHIRPS	Climate Hazards Center Infrared Precipitation with Stations
CLM	Common Land Model
CMIP	Coupled Model Intercomparison Project
CNRM	Centre National de Recherches Météorologiques
CSR	Center for Space Research
CRI	Climate Risk Index
CWSA	Canopy Water Storage Anomaly
DA	Data Assimilation
DD	Dynamic Downscaling
ERA5	ECMWF Reanalysis, 5th Generation
ET	Evapotranspiration
FDM	Finite Difference Method
FEFLOW	Finite Element subsurface FLOW
FIM	First Inter-Monsoon
GCM	General Circulation Model
GFZ	German Research Centre for Geosciences (GeoForschungsZentrum)
GIA	Glacial Isostatic Adjustment
GLDAS	Global Land Data Assimilation System
GNN	Graph-based Neural Networks
GRACE	Gravity Recovery and Climate Experiment
GRACE-FO	Gravity Recovery and Climate Experiment Follow On
GWL	Groundwater Level
GWLA	Groundwater Level Anomaly
GWS	Ground Water Storage
GWSA	Ground Water Storage Anomaly
IPCC	Intergovernmental Panel on Climate Change
JPL	Jet Propulsion Laboratory
LightGBM	Light Gradient Boosting Machine

LSMs	Land Surface Models
LST	Land Surface Temperature
LSTM	Long Short-Term Memory
ML	Machine Learning
MLR	Multiple Linear Regression
MODFLOW	Modular finite-difference groundFLOW
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NDVI	Normalized Difference Vegetation Index
NEM	Northeast Monsoon
PDE	Partial Differential Equation
PINN	Physics-Informed Neural Network
Pr	Precipitation
R^2	Coefficient of Determination
RF	Random Forest
RRE	Richards Equation
RMSE	Root Mean Square Error
SEML	Stacking Ensemble Machine Learning
SD	Statistical Downscaling
SIM	Second Inter-Monsoon
SMSA	Soil Moisture Storage Anomaly
SSP	Shared Socioeconomic Pathways
SRTM	Shuttle Radar Topography Mission
SUTRA	Saturated-Unsaturated TRAnsport
SWEA	Snow Water Equivalent Anomaly
SWM	Southwest Monsoon
SWSA	Surface Water Storage Anomaly
TWS	Total Water Storage
TWSA	Total Water Storage Anomalies
VIC	Variable Infiltration Capacity
WGHM	WaterGAP Global Hydrology Model
WRB	Water Resources Board
XGBoost	eXtreme Gradient Boosting