Predicting Groundwater Drought in Ireland Using a Machine Learning Ensemble

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Groundwater drought in temperate regions remains an understudied research area, despite its growing significance. Projected changes in rainfall intensity, frequency, and duration are expected to increase drought risk, highlighting the need for improved monitoring. However, defining and predicting groundwater drought poses significant challenges, particularly in Ireland's temperate climate and complex hydrogeology. This study aims to understand groundwater drought by: (1) evaluating existing drought indicators to better define groundwater drought; (2) characterising groundwater response to climate extremes (e.g., drought); (3) developing machine learning models to forecast the occurrence of drought events.

1. Methodology

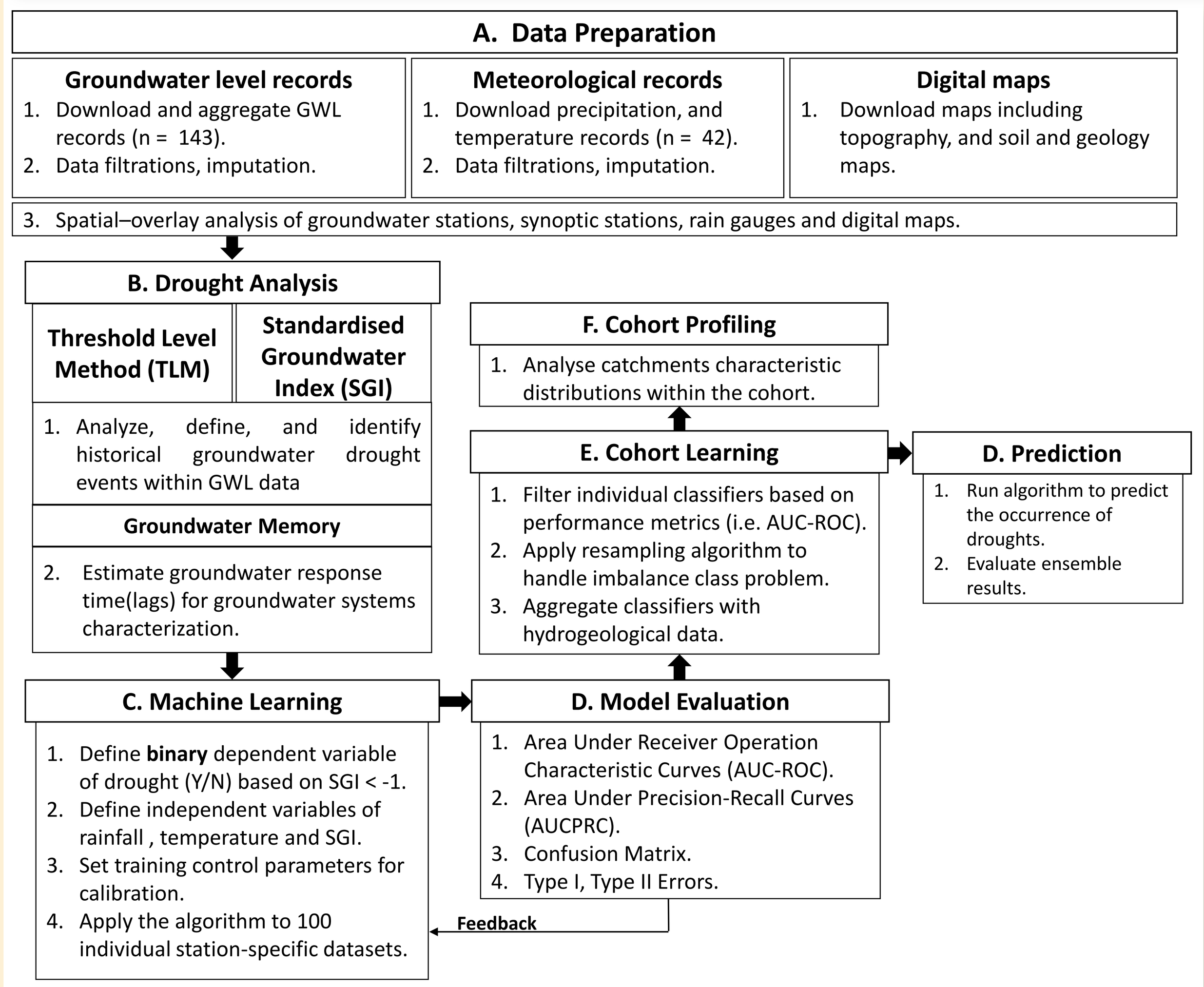


Fig. 1. Workflow for defining and predicting groundwater drought events in the Republic of Ireland (ROI).

2. Groundwater Drought Analysis

What defines Groundwater Drought ?

- Groundwater droughts are complex phenomena to define, understand and predict due to the interplay of natural (e.g. climate change) and anthropogenic pressure (e.g. pumping) .
- Aquifers vary greatly in their geology, hydrology, surface water hydrology and subsoil characteristics, particularly in the heterogeneous region like Ireland.
- There is no single, universally accepted indicator to characterise drought due to the diverse nature and response of groundwater systems to stressors.

Standardized Groundwater Index (SGI)

- The Standardized Groundwater Index (SGI) is a widely used tool for identifying and monitoring groundwater drought based on groundwater level time series.
- SGI transforms groundwater level data into a standardized normal distribution using a non-parametric approach.
- It is favored for its ability to standardize values across different aquifer systems, allowing for comparison between groundwater environments.
- The SGI was evaluated over differing SGI thresholds to characterise droughts, using the 2018 summer drought for validation. A threshold of -1.0 SGI was found to be suitable for analyses.

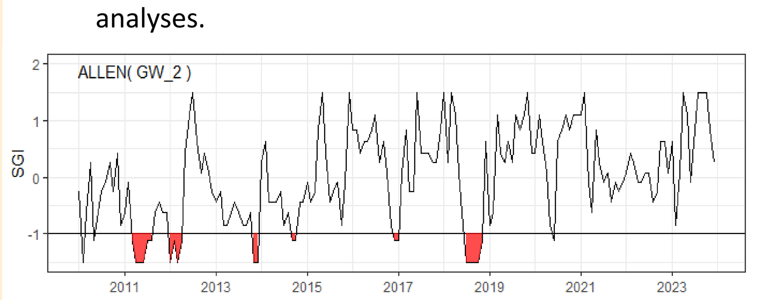


Fig. 2. Calculated time series of the Standardized Groundwater Index (SGI) for the monitoring station (*ALLEN)*. Groundwater drought episodes are indicated in red and represent periods where SGI < -1.

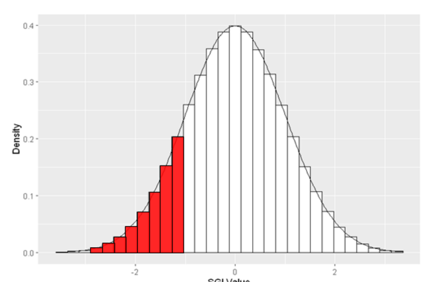


Fig.3. The Distribution of the Standardised Groundwater Index.

3. Results

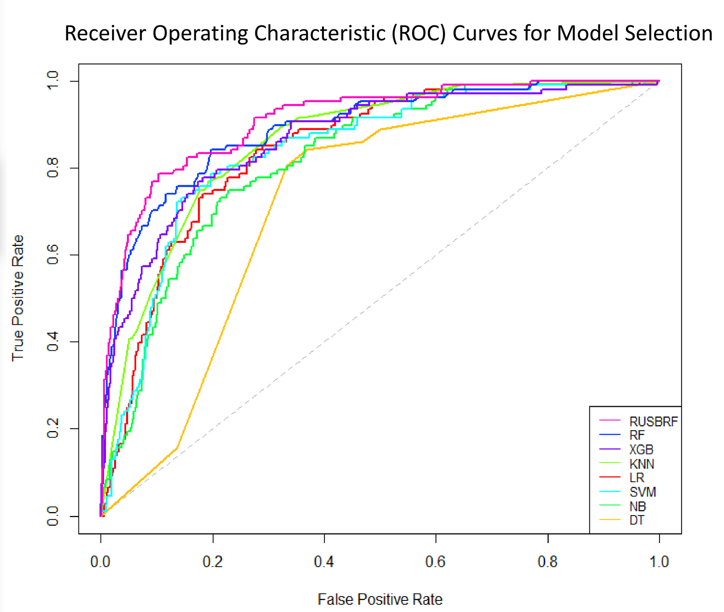
How were classifiers evaluated and classified?

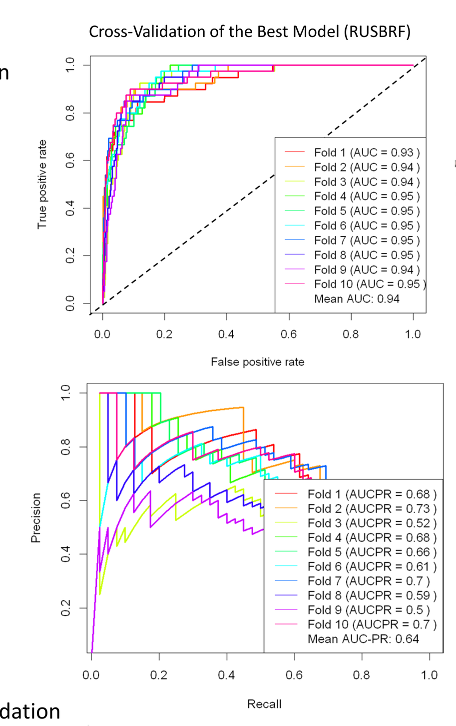
- The Area Under the Receiver Operating Characteristic Curve (AUC-ROC) was used to evaluate classifier performance, resulting in a wide range of AUC-ROC values.
- A threshold of ROC > 0.8 was applied to distinguish between classifiers' performance: classifiers with AUC-ROC values above 0.8 were classified as *top-performing*, while those below the threshold were considered *moderate-performing*.

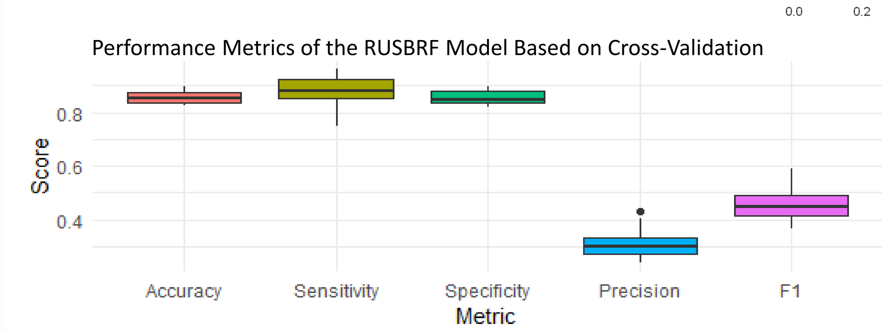
What characterises top-performing classifiers' "cohort"?

- Short groundwater memory (p=0.005).
- High groundwater-drought sensitivity.
- Diverse subsoil (p= 0.04) and bedrock (p=0.03) category.

① Short Groundwater Memory System







Why are precision and F1 scores lower than other parameters?

- "True" drought hard to predict due to multifaceted drivers (natural, anthropogenic), resulting in high false positive rates.
- Droughts are rare events, resulting in imbalanced datasets that challenge classification models.

Map Legend

- *Short GW memory System (Top Performing classifiers)*
- *Moderate to long GW memory System (Moderate Performing classifiers)*

Base map - Bedrock Aquifer (GSI)

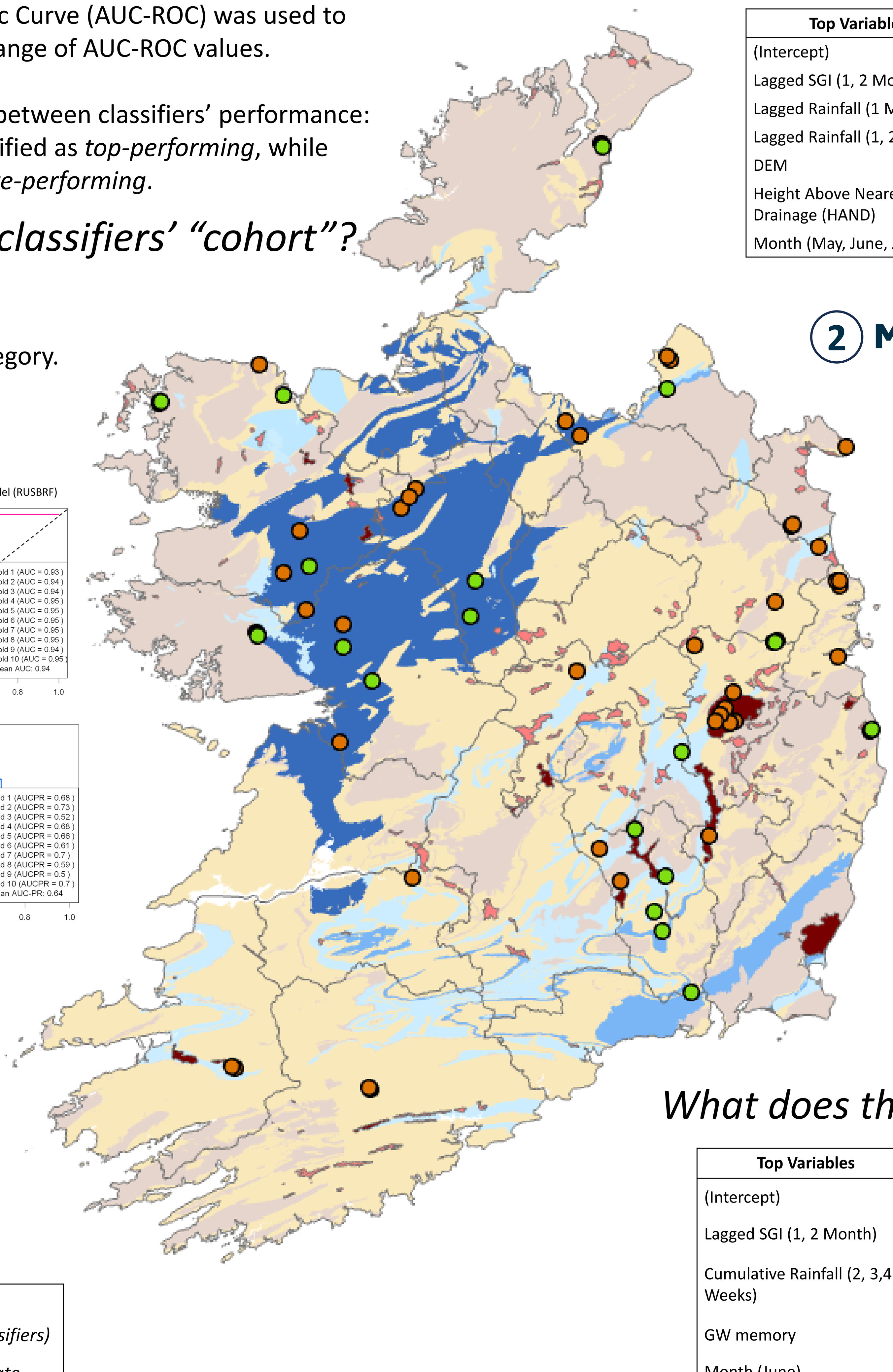
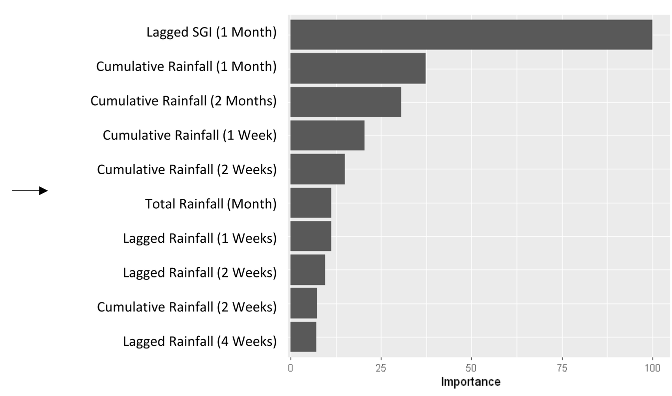


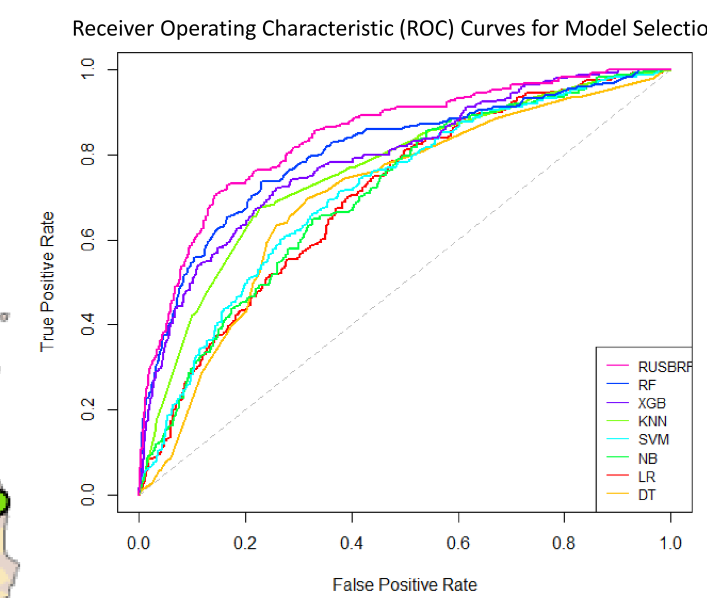
Fig.4. Map of the Republic of Ireland (ROI), indicating the location of the study areas referred to in this work.

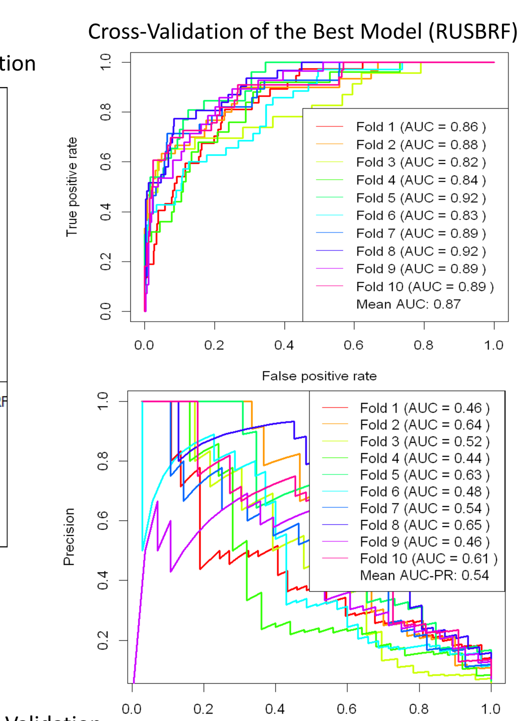
What does the models indicate (logistic Regression and Random Forest) ?

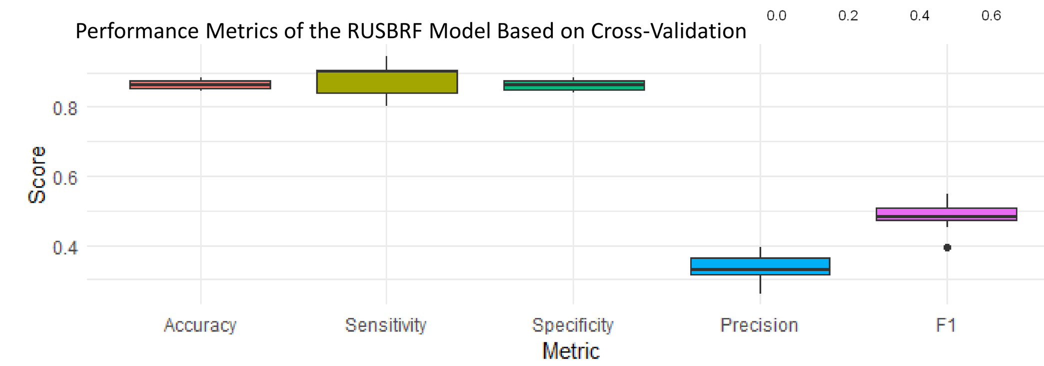
Top Variables	β	p-value
(Intercept)	-0.70	<0.001
Lagged SGI (1, 2 Month)	-2.2, -0.8	<0.001
Lagged Rainfall (1 Month)	-4.5	<0.01
Lagged Rainfall (1, 2 Weeks)	1.8, 1.6	<0.01
DEM	-1.43	<0.01
Height Above Nearest Drainage (HAND)	1.26	<0.05
Month (May, June, July)	1,0.8,0.8	<0.05



② Moderate - Long Groundwater Memory System

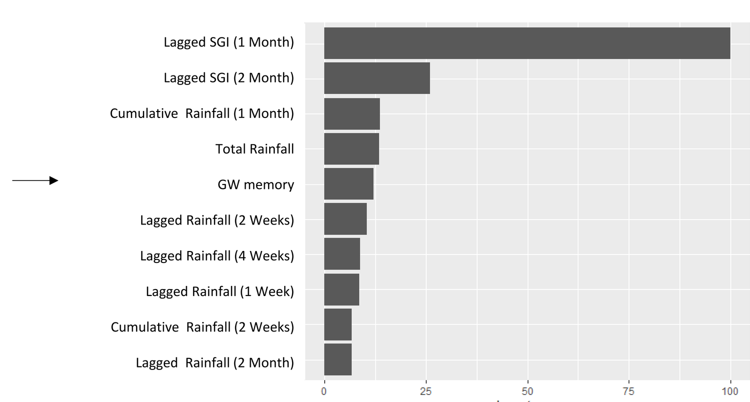






What does the models indicate (logistic Regression and Random Forest) ?

Top Variables	β	p-value
(Intercept)	-0.39	<0.001
Lagged SGI (1, 2 Month)	-2.0 ,-0.61	<0.001
Cumulative Rainfall (2, 3,4 Weeks)	-1.5,-1.0, -0.92	<0.001
GW memory	-3.2	<0.01
Month (June)	0.7	<0.01



4. Conclusions

- Random Under-Sampling Boosted Random Forest (RUSBRF) model shows superior performance to baseline models, like Logistic Regression (LR), Decision Trees (DT) and K-Nearest Neighbours (KNN) across both groundwater systems.
- In *short groundwater system*, RUSBRF achieved 88.6% accuracy, 90% sensitivity, 88.5% specificity, 96.4% AUC ROC and 65% AUC PRC.
- In *moderate-long groundwater memory system*, RUSBRF achieved 86.8% accuracy, 88.4% sensitivity, 86.7% specificity, 94.5% AUC ROC and 64.7% AUC PRC.
- Model interpretation of the short memory system aligns effectively with its behaviour, as it shows the importance of one-month lagged SGI, indicating short drought propagation.
- In moderate-long memory systems, analysis shows the importance of two-month lagged SGI, indicating a longer drought history.
- Variable analysis from logistic regression reveals that droughts are most likely to occur in summer months, May, June, July, in the *short memory system* and in June in the *moderate-long*.