ASSESSMENT OF AGRICULTURAL AND METEOROLOGICAL DROUGHT DYNAMICS IN ASSOCIATION WITH GROUNDWATER STRESS

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ABSTRACT

Over the years, Bangladesh has faced significant drought events, which have far-reaching consequences on agricultural productivity and groundwater table. The effects are prominent in the northwest part of the country that experiences hot, humid, arid climatic condition. The Rajshahi crop zone is the part of the region highly suceptible to drought. In the study, the dynamics of long-term agricultural and meteorological drought and their interaction with groundwater level were assessed during Rabi Season (December-January). Standardized Precipitation Evapotranspiration Index (SPEI), Soil Wetness Deficit index (SWDI), and Vegetation Health Index (VHI) are the most popular indices to estimate the drought conditions from 2000 to 2023. The study reveals that SPEI effectively quantified wet and dry years, however, several normal SPEI years exhibited drought conditions in VHI, which identified the influence of thermal condition and and soil moisture. The reduced vegetation stress as well as healthy vegetation cover were recorded in the study area from 2017-2018 to 2022-2023, where irrigation was suitable. Likewise, SWDI showed declining soil moisture deficit after 2014, reflecting the expansion of intensive irrigation practices during Rabi season. Despite this improvement in soil moisture, pre-monsoon and post-monsoon groundwater levels experiencd significant depletion in the same time frame. During 2023 the depletion was at 14.95m bgl for pre-monsoon and 9.14m bgl post-monsoon period. The Mann-Kendall test confirmed these patterns, with a Z-value of -4.007, -3.47, and -3.79 for SWDI, Pre-monsoon and post-monsoon groundwater level, respectively. It was observed that enhanced moisture level in soil and significant groundwater depletion in the Rabi season, highlighting growing reliance on groundwater resources. These insights underscore the urgent need for climate-adaptive agricultural practices to ensure long-term groundwater sustainability and regional food security.

Keywords: *Agricultural drought, Meteorological drought, Rajshahi Crop zone, Groundwater level*

1. INTRODUCTION

Drought, a catastrophic natural hazard caused by prolonged low rainfall, triggering widespread water scarcity and hydrological imbalances (Ozelkan et al., 2016). It is influenced by various factors like irregular rainfall patterns, excessive use of water resources and high rates of evapotranspiration. A deficit in rainfall gives rise to meteorological drought, while lack of adequate soil moisture leads to agricultural drought, subsequently reducing surface runoff. Bangladesh experiences drought in an alarming rate, about twice per decade. It substantially reduce groundwater recharge and disruptions to food security in the crop zones (Mondol et al., 2021). The Rajshahi crop zone, which includes Barind tract is highly vulnerable to drought conditions (Alamgir et al., 2020).

Droughts assessment includes multiple indices to evaluate drought severity and intensity (Mishra & Singh, 2011). Standardized Precipitation Evapotranspiration Index (SPEI) is a commonly used indicator to integrate precipitation and evapotranspiration data across multiple time scales, which portraying meteorological droughts (Kaur et al., 2022). Moreover, Vegetation Health Index (VHI) is the satellite-driven index valuable for monitoring agricultural droughts and combines Vegetation Condition Index (VCI) and Thermal Condition Index (TCI). It reflects soil moisture and vegetation stress, which is key to assess drought intensity. During droughts, reduced soil moisture and elevated surface temperatures intensify evapotranspiration, causing seasonal water stress (Kukunuri et al., 2022). To quantify the water stress, Soil Wetness Deficit Index (SWDI) is effective in the assessment of drought severity and vegetation water balance in the dry season (Keshavarz et al., 2014). The recurring soil moisture deficit have increased the reliance of farmers on groundwater for irrigation. Over the past decades, groundwater has become the dominant water source in northwest Bangladesh due to the expansion of Rabi crops. Limited surface water and widespread use of deep and shallow tube wells have led to over-extraction of groundwater (Mainuddin et al., 2019). These phenomena underscore the importance of evaluating drought impacts on groundwater resources. Previous studies have mainly focused on individual drought indicators, with limited attention to the interaction between drought conditions and groundwater decline (Hao & Singh, 2015; Saha et al., 2021). This study aims to examine how the changing drought patterns influence groundwater levels during the Rabi season. The objectives are to: (1) evaluate the meteorological and agricultural drought impacts in Rajshahi crop zone, and (2) analyze the trend of agricultural water stress and groundwater depth.

2. METHODOLOGY

2.1 Study Area

The Rajshahi crop zone is under the northwest part of Bangladesh. It covers four districts such as Rajshahi, Noagoan, Chapai Nawabganj, and Natore, incorporating 25 Upazilas. The study area is located between the latitude 24°08' N to 25°13'N and the longitude 88°01'E to 89°10'E (Figure 1). It has dry and humid agroclimatic conditions with an area of 8371 km^2 area. The annual precipitation ranges between 1273mm to 2515mm, whereas the monsoon rainfall varies 1428mm. During summer and winter season, the average temperature is recorded as 25°C-35°C, 9°C-15°C, respectively. The evapotranspiration rate is 1309mm, which make this region the driest area of Bangladesh (Akhter et al., 2019).

2.2 Data Collection

Station data for assessing meteorological drought and groundwater level was utilized in the study. Monthly rainfall and temperature data from six BMD (Bangladesh Meteorological Department) stations were collected to compute SPEI index from 2000 to 2023. Moreover, Groundwater data were collected from the Bangladesh Water Development Board (BWDB). The data was examined for pre-monsoon (April) and post-monsoon (October) periods to assess seasonal groundwater stress during Rabi season between 2000-2023. To evaluate the agricultural drought, MODIS-derived satellite products were processed in Google Earth Engine (GEE) from the year 2000 to 2023.

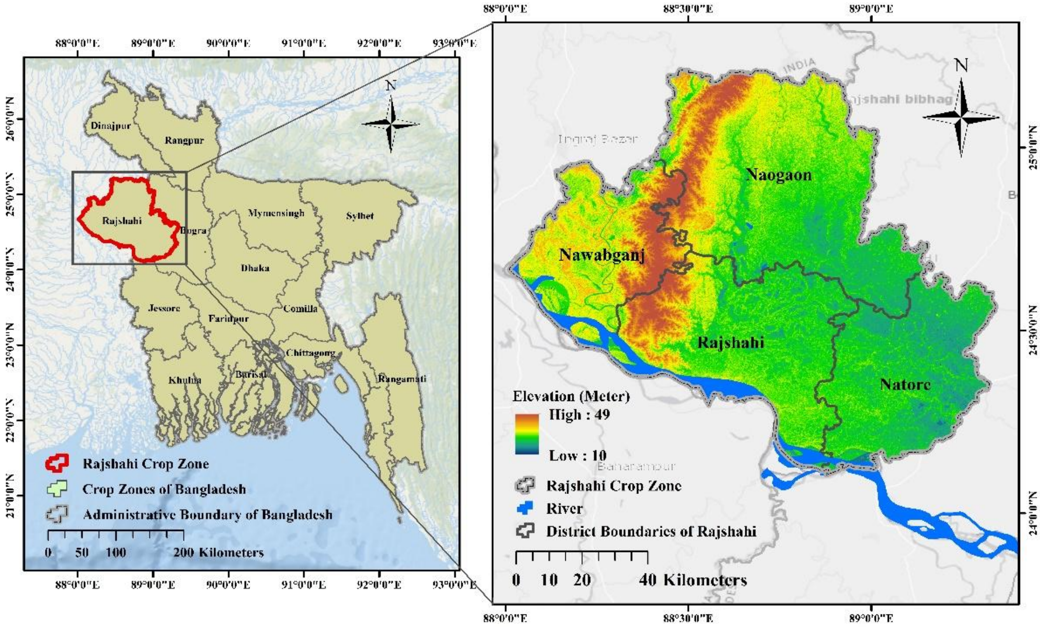

Figure 1: Rajshahi Crop Zone

2.3 Assessment of Multiple Drought Conditions

Monthly rainfall and temperature data were used to identify drought occurrences. For seasonal analysis during Rabi Season, seasonal SPEI (December-March) was computed using data from 2000-2023. The analysis was conducted using the SPEI package in R, which incorporates both precipitation and potential evapotranspiration (PET) (Beguería et al., 2014). Hargreaves method was used to estimate PET, as it requires minimum and maximum value of monthly temperature data. The monthly water deficit was computed by the difference between rainfall and PET. SPEI employed log logistic distribution of three parameters, which was standardized to capture the variability of climatic water balance. The probability function *f(x)* was obtained and transformed into standardized normal variable to derive SPEI value equation (1). Parameters *α, β,* and *γ* denote the scale, shape, and location, estimated through L-moment equations involving gamma function Γ and w_0, w_1, and w_2 L-moments in the equation (2)-(4).

$$f(x) = \frac{\beta}{\alpha}\left(\frac{x-\gamma}{\alpha}\right)^{\beta-1}\left(1+\left(\left(\frac{x-\gamma}{\alpha}\right)^{\beta}\right)\right)^{-2} \tag{1}$$

$$\alpha = \frac{(w_0-2w_1)\beta}{\Gamma\left(1+\frac{1}{\beta}\right)\Gamma\left(1-\frac{1}{\beta}\right)} \tag{2}$$

$$\beta = \frac{2w_1-w_0}{6w_1-w_0-6w_2} \tag{3}$$

$$\gamma = w_0 - \alpha.\Gamma\left(1+\frac{1}{\beta}\right)\Gamma\left(1-\frac{1}{\beta}\right) \tag{4}$$

The cumulative probability function is defined as the equation (5) and further standardize by the equation (6). In the equation, the constants are c_0= 2.515517, c_1= 0.802853, c_2=0.010328, d_1= 1.432788, d_2= 0.189269, d_3= 0.001308. In this study, SPEI values were ranging from below -2 to above +2 as extreme drought to no drought.

$$F(x)\frac{1}{1+\left(\frac{\alpha}{x-\gamma}\right)^{\beta}} \tag{5}$$

$$SPEI = W - \frac{C_0-C_1w+C_2w^2}{1+d_1w+d_2w^2-d_3w^3} \tag{6}$$

Furthermore, Agricultural drought indices comprise seasonal vegetation and water stress indices. VHI is a composite indicator for assessing vegetation condition (Sun & Kafatos, 2007). It was derived from two components: VCI and TCI, which are expressed in equation (7)-(9). The value of α defines the relative importance of VCI and TCI. NDVI is demarcated as Normalized Difference Vegetation Index and LST as Land Surface Temperature. VHI values were classified to delineate vegetation condition.

$$VHI = \alpha \times VCI + (1 - \alpha) \times TCI \tag{7}$$

$$VCI = \frac{\mathrm{NDVI} - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \tag{8}$$

$$TCI = \frac{LST_{max} - LST}{LST_{max} - LST_{min}} \tag{9}$$

SWDI is widely used indicators for assessing agricultural drought. It is derived from Soil Wetness Index (SWI). The index is calculating using the formula (equation 10), estimating moisture variability using triangular space relationship between NDVI and LST (Keshavarz et al., 2014):. In the equation, $T_s(i)$ is the LST of pixel *i* and T_{max} and T_{min} represent the maximum and minimum LST values along the dry and wet edges (equation 11 and 12).

$$\mathrm{SWI_i} = \left(\frac{\mathrm{T_{max}}\ (i) - \mathrm{T_s}\ (i)}{\mathrm{T_{max}}\ (i) - \mathrm{T_{min}}\ (i)} \right) \tag{10}$$

$$\mathrm{T_{max}}\ (i) = b + a \times \ \mathrm{NDVI\ (i)} \tag{11}$$

$$\mathrm{T_{min}}\ (i) = d + c \times \ \mathrm{NDVI\ (i)} \tag{12}$$

The soil moisture deficit (SD_i) for each 8-day period is then computed as equation (13) and cumulative deficit is derived from consecutive dry periods. Finally, SWDI is measure using the equation (14).

$$\mathrm{SD_i} = \left(\frac{\mathrm{SWI_i} - M\mathrm{SWI_j}}{max\mathrm{SWI} - \mathrm{min}\, SWI} \right) \times 100 \tag{13}$$

$$\mathrm{SWDI_i} = \left(\frac{\sum_{t=1}^{i} \mathrm{SD_t}}{25t + 25} \right) \tag{14}$$

2.4 Trend Analysis of Groundwater Level and SWDI

The temporal groundwater trends and SWDI from 2000-2023 were examined. It illustrates the trend of agricultural water stress and groundwater level over 17-years' time period. The Mann-Kendall test (Mk test) identified the significance and direction of trends for its robustness against non-normally distributed data and outliers (Yilmaz, 2019).

3. RESULTS AND DISCUSSION

3.1 Analysing Seasonal SPEI Trends

The computation of SPEI for the Rabi season are displayed in the Figure 2 from 2000-2001 to 2022-2023. The years 2005-2006, 2009-2010, and 2020-2021 were identified as the driest periods indicating the occurrence of extreme drought conditions. During the monsoon season (June-September), the years of 2009 and 2020 was recorded lowest rainfall, which was near zero during October and November. Consequently, the soil moisture reserves were insufficient for evapotranspiration during the following Rabi season, which lead strongly negative water balance and low negative SPEI values. This highlights the dominant role of monsoon rainfall and post monsoon recharge in determining dry-season moisture availability in the Rajshahi crop zone. Conversely, positive SPEI values were observed during the years

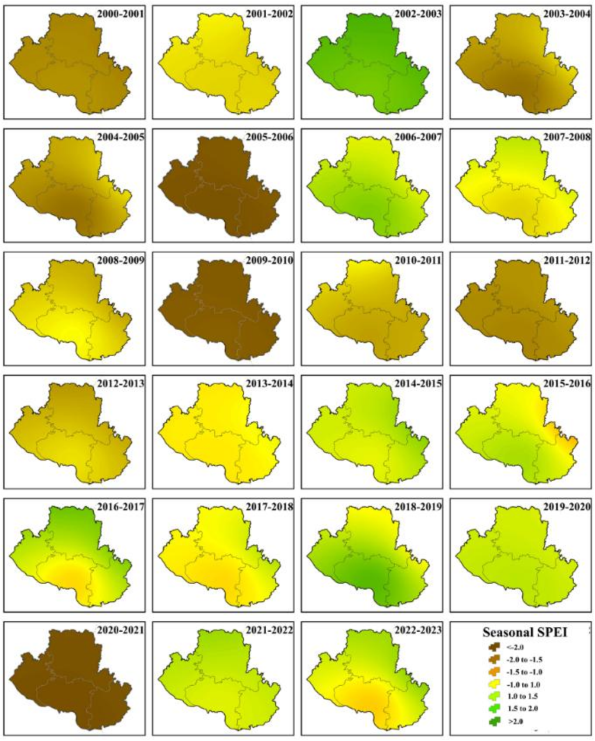

Figure 2: Spatio-temporal Pattern of Seasonal SPEI

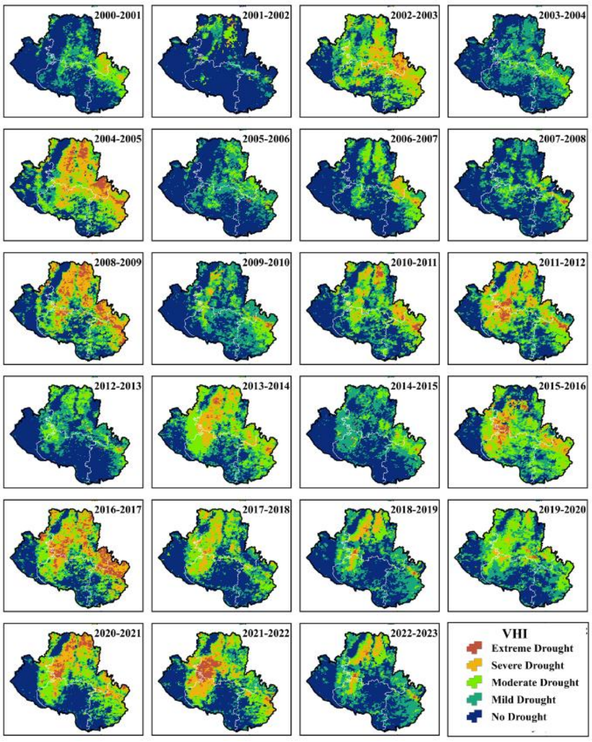

Figure 3: Spatio-temporal Pattern of VHI

2002-2003, 2006-2007, 2016-2017, and 2018-2019. These years were characterized by near normal monsoon rainfall and post-monsoon rainfall (October -November), which resulting in lower potential evapotranspiration during Rabi season. Moderate to high rainfall patterns were recorded for the years 2002 and 2018, leading to positive water balance. In addition, fog and cloud over during the dry years might reduce the incoming solar radiation and low evapotranspiration.

3.2 Vegetation Stress Calculation by VHI

Unlike seasonal SPEI, VHI reflects the agricultural drought stress and calculated using NDVI and LST data from 2000-2001 to 2022-2023 (Figure 3). In year of 2005-2006 and 2009-2010, negative SPEI values coincide with low to moderate vegetation stress. On the contrary, positive SPEI values were associated with severe drought conditions in some areas of Rajshahi crop zone for the years 2002-2003 and 2016-2017. Thus, SPEI cannot fully capture the vegetation drought condition during the Rabi season as it failed to evaluate the thermal condition and greenness of vegetation like VHI. Futhermore, the spatio-temporal maps of VHI exhibited low to moderate drought conditions in the areas of low elevation. During dry years, extensive irrigation and available soil moisture coming from preceding monsoon rainfall can improve the VHI value. However, a persistent agricultural stress was observed in the areas with high elevation called Barind tract from the year 2017-2018 to 2022-2023 (Figure 1). The elevated topography accelerates surface runoff rather than water infiltration during the Rabi season. Moreover, dendritic drainage patterns and semi-permeable clay loam limit the natural recharge (Hasan et al., 2022).

3.3 Evaluating Water Stress by SWDI

Figure 4 represents the spatio-temporal variability of SWDI, which provide valuable insights of agricultural drought occurrences by reflecting variations in soil moisture. The Rajshahi crop zone exhibited the most pronounced soil water deficits up to the 2012-2013 season. But the soil water deficit had reduced from 2014 to 2023, which can be linked to intensive irrigation practices and minimized plant water stress. Factors such as variations in temperature, atmospheric CO_2, application process of fertilizer and concentration of tropospheric ozone (O_3) can also influence the process.

3.4 Trend Analysis of Groundwater and SWDI

Groundwater levels in the Rajshahi crop zone declined noticeably in the pre-monsoon and post-monsoon seasons from 2000 to 2023 (Figure 5). During the pre-monsoon period (April), the mean groundwater depth was found as 7.9m bgl to 12.8m bgl for the years 2001 and 2016, respectively, which was further declined to 14.95m bgl during 2023, indicating a lowering trend of groundwater table.

In the post-monsoon period, the groundwater levels also declined, though the rate was less steep. The mean depth was about 3.4m bgl in 2001, which was recorded stable until 2005. After 2005, there was a gradual decline in 2007 as 4.82m bgl and 8.72m in 2011. However, from 2012 the graph is remained unchanged until 2015. After the timeframe, the water table was plunged to around 9.14m bgl during 2023. The results portray that after monsoonal recharge, the aquifer did not fully recover due to groundwater dependency.

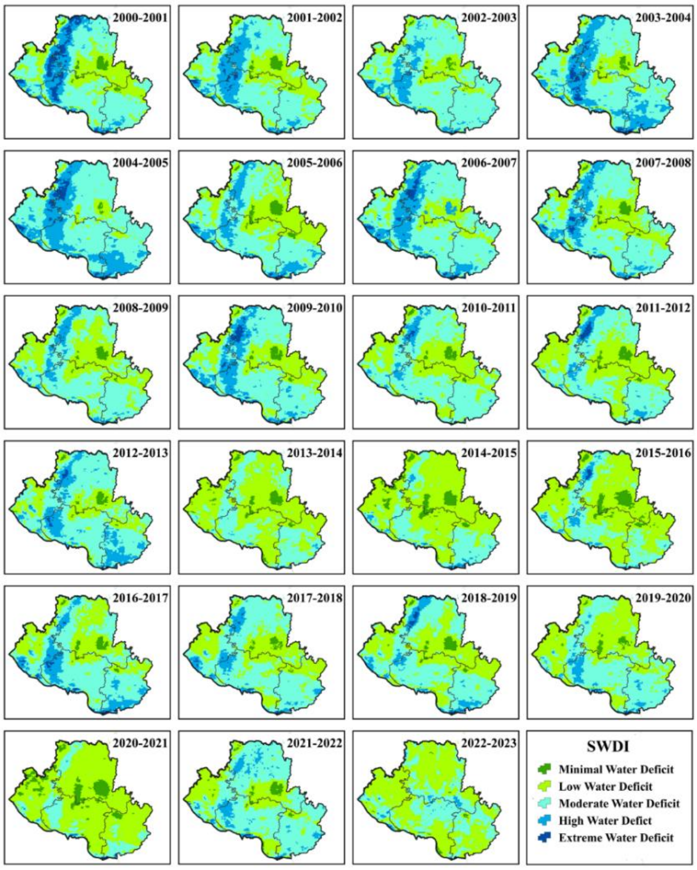

Figure 4: Spatio-temporal Pattern of SWDI

A downward trend was observed in the SWDI, suggesting alleviation of vegetation stress over time. The level of groundwater reduced, nevertheless, the soil moisture availability enhanced. The pattern of water deficit depicts adequate the crop water requirements, though groundwater reserves continued to deplete across the Rajshahi crop zone (Figure 5). Over-exploitation of groundwater resources result in this phenomenon. To evaluate the trends, Mann-Kendall test shows statistically significant values, where -4.007 indicates improvements in soil moisture conditions. Similarly, the negative Z-value for groundwater level during pre-monsoon and post-monsoon as -3.4667 and -3.7857, respectively, confirms significant decline in groundwater level.

The study portray that the Rajshahi Crop zone is highly vulnerable to variations in monsoon rainfall and post-monsoon recharge. The erratic rainfall pattern is responsible for lack of soil moisture and groundwater recharge during Rabi season. These findings also suggest that irrigation practice can reduce the stress temporarily during Rabi season, however, groundwater depletion is prominent and poses a long-term sustainability concern.

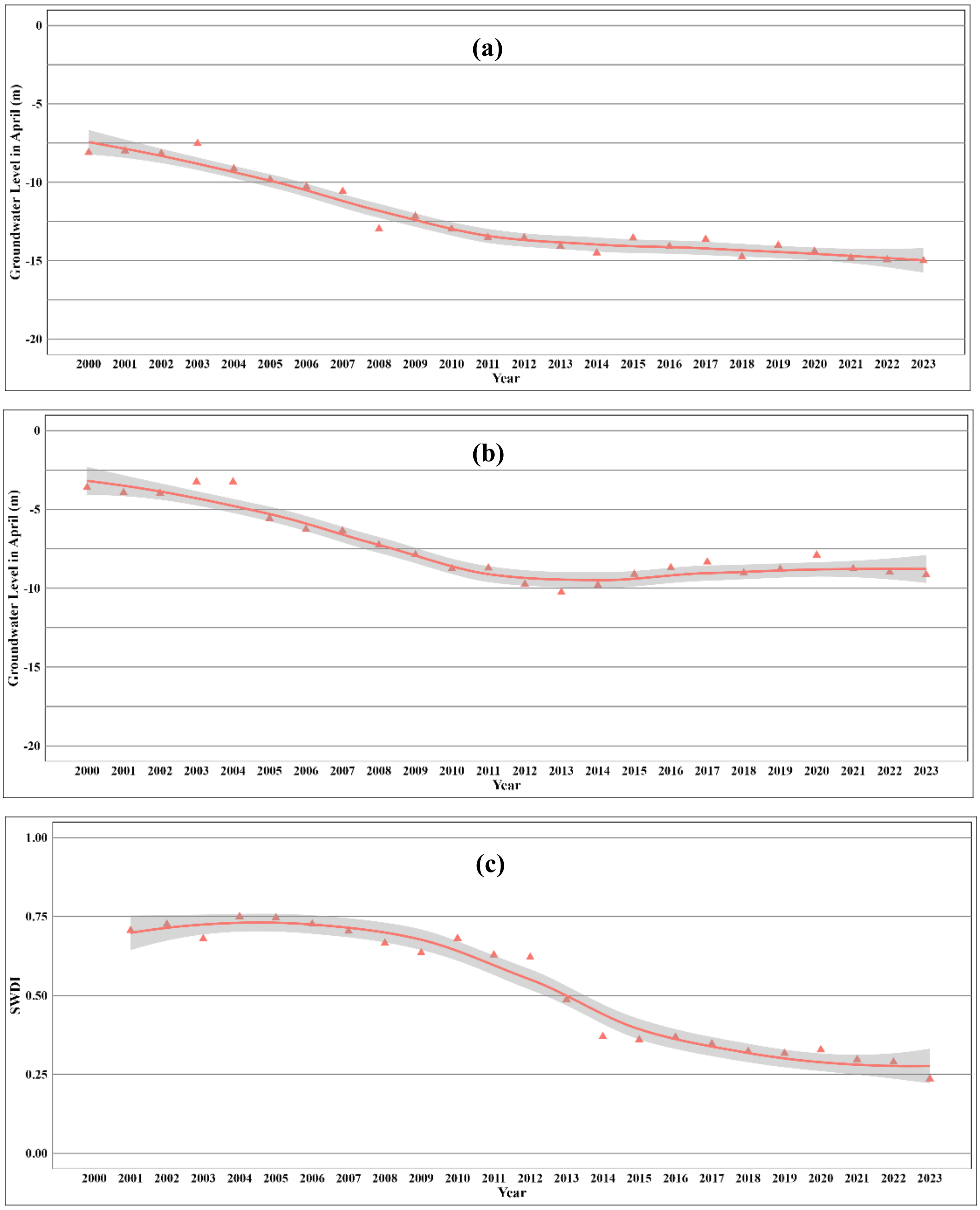

Figure 5: Trend Analysis of (a) Pre-monsoon Groundwater , (b) Post-monsoon Groundwater and (c) SWDI

4. CONCLUSIONS

The research is focused on the long-term trend of drought conditions, soil moisture availability and groundwater level. The important insights of the research are: (i) seasonal SPEI identified the dry and wet conditions based on rainfall and evapotranspiration. However, normal SPEI condition was also recorded as drought condition in VHI analysis. This finding suggests that Rabi season drought cannot be defined by SPEI alone as soil moisture condition and temperature stress also influence agricultural drought; (ii) VHI showed a significant vegetation stress in the Barind tract, characterized by higher elevation, limiting soil moisture retention. However, good vegetation condition was observed in comparatively lower elevated area. Similarly, SWDI indicates consistent low water deficit after 2014 during Rabi season, due to intensive irrigation practices, maintaining soil moisture and reducing short-term vegetation stress; (iii) a substantial depletion in pre-monsoon and post-monsoon periods was prevalent across the study area. The extent of irrigation in the area makes it vulnerable to store sufficient groundwater recharge. Though the downward trend of SWDI shows improved vegetation condition and soil moisture, excessive reliance on groundwater resources is not regarded as suitable water management practice and it have a drastic long-term effect on the depletion of groundwater table of Rajshahi crop zone. Improved water governance and efficient irrigation method have contributed to balance the withdrawal and recharge of groundwater and ensure agricultural resilience.

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Declaration of Use of AI

AI tools were not used in the study to generate the research conceptualization, resources, methodology, formal analysis, interpretation and visualization. The authors ensure the originality and integrity of the manuscript.

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