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Investigation of Hydrological Drought in Central Dry Zone, Myanmar

Poe Zar Ni Aung[1], Nilar Aye[2], Yin Yin Htwe[3]
poezarniaung@gmail.com[1], dnilaraye@gmail.com[2], yinyinhtwecivil@gmail.com[3]
[1]Ph.D candidate, Department of Civil Engineering, Mandalay Technological University
[2]Professor, Department of Civil Engineering, Mandalay Technological University
[3]Associate Professor, Department of Civil Engineering, Mandalay Technological University

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Abstract

This study presents the investigation of hydrological drought in Myanmar's Central Dry Zone using the Streamflow Drought Index (SDI) across various timescales (3, 6, 9, and 12 months) to assess its impact on water resources and agricultural productivity. The Central Dry Zone, which includes the Ayeyarwaddy River and encompasses the regions of Sagaing, Mandalay, and Magway, shows significant vulnerability of hydrological extremes due to its semi-arid climate and dependence on water resources. Monthly discharge data from selected hydrological stations from 1993 to 2022 is analyzed using DrinC 1.7 software to derive SDI values and drought characteristics. The results show that critical drought events in 2005-2006, 2013-2015, and 2019-2021 for all stations are marked by high severity and extended duration. Short-term SDI (SDI 3 and SDI 6) values capture rapid, intense droughts, while long-term SDI (SDI 9 and SDI 12) highlight extended water shortages. From this result, Monywa station shows the highest severity and duration of droughts across all SDI timescales compared to other stations. The results underscore the necessity of strategic water management and drought mitigation measures to protect agriculture and guide planning, establish early warning systems, and support sustainable development in the Central Dry Zone, Myanmar.

A. Introduction

Drought is a natural disaster, which has significant and widespread impacts especially on people and many economic sectors, and its severity and frequency are increasing due to the global warming [1]. Drought affect very large areas and populations, causing economic and environmental problems, which can lead to irreversible damages [2]. Analysis of drought in terms of water resources management is crucial. Drought has been sorted into four types: meteorological, hydrological, agricultural and socio-economic droughts. Hydrological drought indeed tends to occur later than meteorological drought. Hydrological extreme events both flood (high flow) and drought (low flow) are the most concerning issues in the world [3]. However, drought is one of the most common natural disasters that have a great negative impact on agriculture and water resources projects in a wide range [4]. Many of these effects are associated with hydrological drought. Hydrological drought is a natural hazard that occurs when there is a significant reduction in water availability, such as streamflow, reservoirs, lakes and groundwater decline. Hydrological drought should be considered along with the effects of reduced rainfall period. Although the origin of all droughts is the lack of rainfall, which is beyond human control, hydrologists focus most of their attention on ending this phenomenon and this period in the watershed and the hydrological system. The streamflow drought index (SDI) is an important tool used for assessing hydrological drought based on streamflow data. It measures drought conditions by examining the variations in streamflow over time, using different timescales to captured seasonal based on short-term SDI 3, medium-term SDI6, SDI9 and long-term annual based on SDI 12. DrinC 1.7 (Drought Indices Calculator) is a free software package that helps users calculate drought indices and analyze drought condition. The Ayeyarwaddy river is the largest and important river in Myanmar and it has a crucial role in the development of Myanmar's central dry zone. In addition, the Ayeyarwaddy river has been an important trade route, connecting the central dry zone with other parts of Myanmar and neighboring countries. However, the river and its surrounding areas in the central dry zone have been facing hydrological drought in recent years. Hydrological drought in the central dry zone is primarily caused by a combination of natural and human factors. The natural factor include meteorological drought (caused of reduced rainfall) due to climate change which can lead to lower water level in river. Therefore, the main objective of this study is to analyse and characterize hydrological drought in central dry zone based on the Streamflow Drought Index (SDI) using DrinC 1.7 software for a better understanding of its impact on water resources infrastructure development.

B. Research Method

Study Area

The Central Dry Zone is located between latitudes 19° 40' and 22° 50' North, and longitudes 93° 40' and 96° 30' East. It primarily covers three regions—Sagaing, Mandalay, and Magway—and consists of 13 districts, covering a total area of 67,700 km^2, which makes up 10% of Myanmar's total land area. This region lies in the rain shadow of the Rakhine mountain range, resulting in a climate that varies between semi-arid and semi-humid. In central dry zone, the Ayeyarwaddy

River flowing about 270 miles (434.5 km) from north to south through the study area. Surface water resources in this region are primarily regulated with 12 meteorological monitoring stations and 5 hydrological measurement stations. Hydrological data is collected from key stations at Monywa, Chauk, Magway, NyaungU, and Sagaing. Figure 1 illustrates the study area's location.

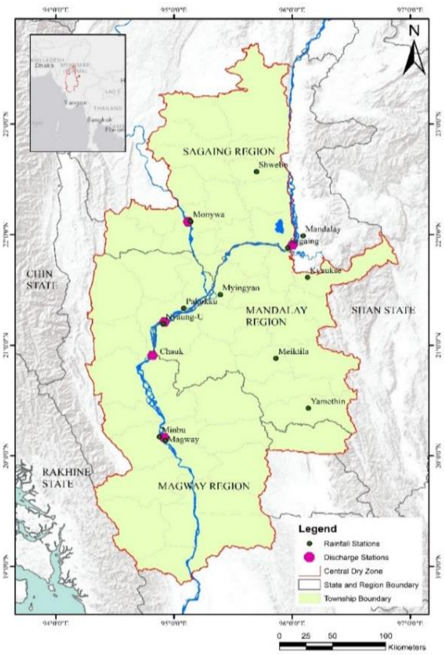

Figure 1. Location of the study area

Material and Method

In this study, monthly discharge data at selected stations was obtained from the department of meteorology and hydrology. Four streamflow stations within the study area have 30 years of recorded data spanning from 1993 to 2022, while NyaungU station provides 20 years of data, covering the period from 2002 to 2022. The Streamflow Drought Index (SDI) was calculated using this monthly discharge data to analyze hydrological drought, utilizing the DrinC 1.7 software.

DrinC 1.7 (Drought indices calculator) is a software package which was developed for providing a simple, though adaptable interface for the calculation of drought indices, meteorological, hydrological and agricultural drought analysis [6].

The Streamflow Drought Index (SDI) was developed by Nalbantis [7], which is used to characterize the streamflow drought conditions. Its calculation is similar to SPI and therefore has the same characteristics of simplicity and efficiency [8]. The SDI is based on monthly observed streamflow volumes at different timescales and thus offers the advantage of controlling streamflow drought in the short, medium and long term. According to Nalbantis (2008), if a time series of monthly streamflow volumes $Q_{i,j}$ is available, in which i denotes the hydrological year and j the month within that hydrological year (j = 1 for October and j = 12 for September), $V_{i,k}$ can be obtained based on the equation:

$$V_{i,k} = \sum_{j=1}^{k} Q_{i,j} \quad i = 1,2, \text{--------}, j = 1, 2, \text{----------}, k = 1,2,3,4 \qquad (1)$$

Where $V_{i,j}$ is the cumulative streamflow volume for the i-th streamflow year and the k-th reference period, $Q_{i,j}$ is monthly streamflow volume at i^{th} streamflow year and j^{th} month within that year.
Based on the cumulative streamflow volumes $V_{i,k}$, the streamflow drought index (SDI) is defined for each reference period k of the i-th streamflow year as follows:

$$SDI = \frac{V_{i,k} - V_{km}}{S_k} \quad (2)$$

Where i = 1,2,------, and k = 1,2,3,4.
V_{km} and S_k are, respectively, the mean and the standard deviation of cumulative streamflow volumes of the reference period k as these are estimated over a long period. According to Nalbantis and Tsakiris, 2009, hydrological drought classification using SDI is shown in Table 1.

Table 1. Drought Classification in SDI Values

SDI Values	Drought Category
≥ 2.0	Extremely wet
1.5 to 1.99	Severe wet
1.0 to 1.49	Moderately wet
-0.99 to 0.99	Near normal
-1.0 to -1.49	Moderately dry
-1.5 to -1.99	Severely dry
< -2.0	Extremely dry

The drought index plays a great role in order to evaluate the consequences of drought impact and to decide various drought characterization, such as duration (D), severity (S), magnitude (M) and relative frequency (RF) [9]. Drought duration is the time taken between consecutive drought events (onset and end of drought). The duration is from starting SDI value equal -1 and turn to a positive SDI value. Drought severity is the summation of negative SDI values from onset to end of a drought event as defined by equation (3). The magnitude of drought is the ratio between drought severity and drought duration, which is defined by equation (4):

$$S_i = -\sum_{i=1}^{D} SDI\ i \quad (3)$$

$$M = \frac{S}{D} \quad (4)$$

The relative drought frequency is the ratio between the number of droughts (n) with negative SDI in drought duration and the total number of drought years in the analysis (N) [10] and Relative Frequency (RF) is defined as

$$RF = \frac{n}{N} \times 100 \quad (5)$$

C. Result and Discussion

The input data for calculating the Streamflow Drought Index (SDI) are monthly streamflow (discharge) data. The generation of SDI timescales for 3, 6, 9, and 12 months was calculated for selected stations using DrinC 1.7 software - corresponding to SDI 3, SDI 6, SDI 9 and SDI 12 respectively. Hydrological drought characteristics, derived from different SDI timescales, are determined using a set of equations, referred to in this study as equations 3, 4, and 5. The results for selected stations are discussed in the subsequent sections. There are four lines representing different SDI timescales: SDI 3, SDI 6, SDI 9, and SDI 12, respectively. Figures 2 to 6 illustrate the generation of SDI timescales for five selected stations. The drought index is essential for assessing the effect of drought and determining various drought characteristics, including duration (D), severity (S), magnitude (M) and relative frequency (RF) for various SDI timescales at the selected stations are presented in Table 2 to 21.

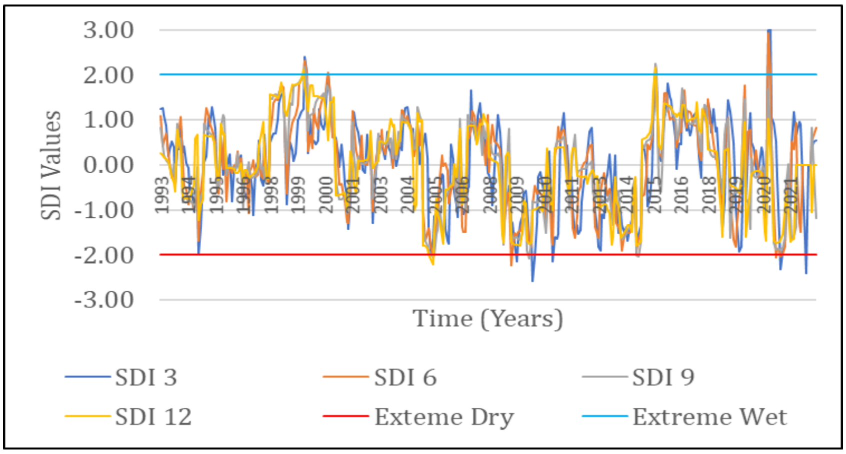

Figure 2. SDI Results for Monywa Station

Figure 2 presents the SDI results for Monywa Station, illustrating a time series plot of the Standardized Drought Index (SDI) values across various timescales from 1993 to 2022. The SDI values range from -3.0 to 3.0, where values below -2.0 signify extreme drought conditions, and values above 2.0 indicate extreme wet conditions. The figure 2 illustrates significant drought periods in 1994, 2010, 2021, and 2022, reflecting severe drought events during these years.

Table 2. Drought Characteristics SDI 3 for Monywa Station

Year	Severity	Duration	Intensity	Relative drought Frequency	Start ~ End
1994	5.99	6	1.00	1.67	July-Dec
1997	1.2	2	0.60	0.56	April-May
2001	2.17	2	1.09	0.56	Aug-Sep
2002	2.11	3	0.70	0.83	Sep-Nov
2005-2006	13.99	12	1.17	3.33	April-March
2006	1.16	1	1.16	0.28	Aug
2006-2007	3.13	4	0.78	1.11	Nov-Feb
2008-2010	28.18	25	1.13	6.94	Sep-Sep
2010-2011	8.01	5	1.60	1.39	Nov-March
2011-2012	8.3	8	1.04	2.22	Nov-June
2012-2013	9.01	8	1.13	2.22	Nov-June
2013-2014	16.83	13	1.29	3.61	Dec-Dec
2018	2.22	2	1.11	0.56	Sep-Oct
2019	5.87	4	1.47	1.11	May-Aug

2020	1.31	1	1.31	0.28	Sep
2021	9.96	7	1.42	1.94	April-Oct
2022	4.08	2	2.04	0.56	June-July

Drought characteristics for Monywa station using the Standardized Drought Index (SDI3) over several years is shown in Table 2. The most severe drought occurred in 2008-2010, lasting 25 months with a total severity of 28.18 and an intensity of 1.13. The second most severe drought was in 2013-2014, lasting 13 months, with a severity of 16.83 and an intensity of 1.29.

Table 3. Drought Characteristics SDI 6 for Monywa Station

Year	Severity	Duration	Intensity	Relative drought Frequency	Start ~ End
1994	2.42	3	0.81	0.83	Oct-Dec
1997	1.24	3	0.41	0.83	Jan-March
2001	3.07	3	1.02	0.83	July-Sep
2002	1.43	2	0.72	0.56	Sep-Oct
2005	14.13	10	1.41	2.78	Jan-Oct
2006	4.35	3	1.45	0.83	Oct-Dec
2008-2010	32.68	28	1.17	7.78	Sep-Dec
2011-2012	5.34	6	0.89	1.67	Nov-April
2012-2015	31.09	29	1.07	8.06	Nov-March
2019	7.01	6	1.17	1.67	Feb-July
2021	11.14	8	1.39	2.22	March-Oct
2022	2.81	2	1.41	0.56	March-April

Table 3 summarizes the characteristics of drought events, using the Standardized Drought Index (SDI) for six-month timescale at Monywa Station. According to the table, the years 2008-2010 and 2012-2015 are critical periods characterized by severe and long-lasting droughts. These events are indicative of potential long-term climate shifts or anomalies that require adaptive management.

Table 4. Drought Characteristics SDI 9 for Monywa Station

Year	Severity	Duration	Intensity	Relative drought Frequency	Start ~ End
1994	2.33	3	0.78	0.83	Oct-Dec
2001	2.47	3	0.82	0.83	July-Sep
2005-2006	24.51	20	1.23	5.56	Jan-Aug
2008	2.42	2	1.21	0.56	Sep-Oct
2009-2010	29.96	24	1.25	6.67	Jan-Dec
2011	1.04	2	0.52	0.56	Sep-Oct
2013-2014	21.75	17	1.28	4.72	Aug-Dec
2019	5.48	7	0.78	1.94	Jan-July
2019	1.42	1	1.42	0.28	Dec
2021-2022	18.95	13	1.46	3.61	Jan-Jan
2022	1.18	1	1.18	0.28	Dec

The drought characteristics SDI 9 for Monywa Station is illustrated in Table 4. At 2009-2010 and 2005-2006, these periods experienced the most severe and prolonged droughts, with severity values of 29.96 and 24.51, respectively. The magnitude of these droughts was high (1.25 and 1.23), and they had substantial RF values (6.67 and 5.56), indicating these were significant and impactful drought events. Years such as 1994, 2001, 2008, 2011, 2019, and 2022 witnessed shorter and less severe droughts, with lower magnitudes and relative drought frequency values, indicating less intense drought conditions.

Table 5. Drought Characteristics SDI 12 for Monywa Station

Year	Severity	Duration	Intensity	Relative drought Frequency	Start ~ End
1994	2.86	3	0.95	0.83	Oct-Dec
2001	1.71	2	0.86	0.56	July-Aug
2004	1.89	2	0.95	0.56	Aug-Sep
2005-2006	22.29	17	1.31	4.72	Jan-May
2008	3.31	2	1.66	0.56	Aug-Sep
2009-2010	25.59	20	1.28	5.56	Jan-Aug
2010	1.01	1	1.01	0.28	Dec
2013-2014	23.05	18	1.28	5.00	July-Dec
2018	2.68	2	1.34	0.56	Aug-Sep
2019-2020	7.71	12	0.64	3.33	Oct-Sep
2021	17.74	12	1.48	3.33	Jan-Dec
2022	1.06	1	1.06	0.28	Oct

Table 5 presents the drought characteristics for Monywa Station over several years, based on the Standardized Drought Index SDI 12. The periods 2009-2010, 2013-2014, and 2021 also recorded the highest relative drought frequency values, indicating more frequent drought conditions during these years. The data for Monywa Station indicates an increase in drought severity and duration over the years, particularly post-2005, across different SDI timescales. The periods of 2008-2010, 2013-2014, and 2021 stand out as years of significant drought events, with high severity, magnitude, and frequency, pointing to potentially worsening climatic conditions.

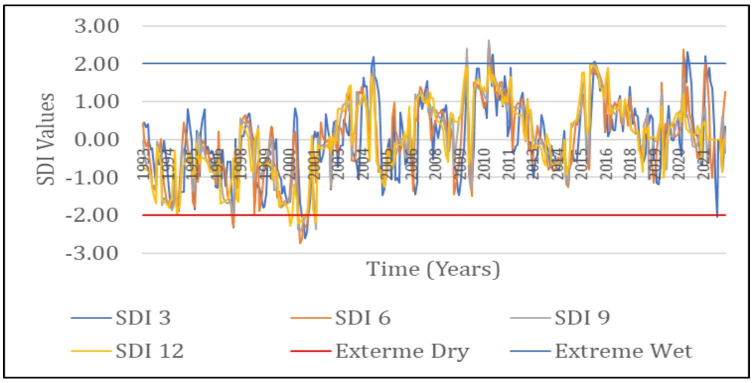

Figure 3. SDI Results for Chauk Station

From figure 3, all SDIs show a significant drop, indicating a period of drought in 1997, 2001 and 2022.

Table 6. Drought Characteristics SDI 3 for Chauk Station

Year	Severity	Duration	Intensity	Relative drought Frequency	Start ~ End
1993-1995	19.54	19	1.03	5.28	Sep-March
1995	3.22	2	1.61	0.56	Aug-Sep
1996-1997	12.23	12	1.02	3.33	Oct-Sep
1997-1998	3.01	3	1.00	0.83	Nov-Jan
1998-1999	13.01	10	1.30	2.78	Oct-July
2000	10.83	8	1.35	2.22	Feb-Sep
2001	15.28	9	1.70	2.50	Feb-Oct
2002	1.33	1	1.33	0.28	Sep
2004	1.06	1	1.06	0.28	Feb
2005	3.75	4	0.94	1.11	May-Aug
2005	1.14	2	0.57	0.56	Oct-Nov
2006	3.24	3	1.08	0.83	Jan-March
2006-2007	3.69	3	1.23	0.83	Dec-Feb
2009	4.73	5	0.95	1.39	March-July
2009-2010	1.3	2	0.65	0.56	Dec-Jan
2013	1.99	4	0.50	1.11	Feb-May
2014-2015	5.5	8	0.69	2.22	Oct-May
2019	3.06	3	1.02	0.83	June-Aug
2022	3.1	2	1.55	0.56	June-July

Table 6 is the most severe drought event occurred from 1993-1995, with a severity of 19.54 and a prolonged duration of 19 months with an intensity of 1.03. Other significant droughts include 2001 (severity of 15.28, duration of 9 months) and 1998-1999 (severity of 13.01, duration of 10 months). Shorter drought events such as 2002, 2004 and 2005 showed lower severity values.

Table 7. Drought Characteristics SDI 6 for Chauk Station

Year	Severity	Duration	Intensity	Relative drought Frequency	Start ~ End
1993	4.55	5	0.91	1.39	July-Nov
1994-1995	16.77	12	1.40	3.33	Feb-Jan
1995-1996	11.07	16	0.69	4.44	Aug-Nov
1997	15.15	12	1.26	3.33	Jan-Dec
1998-1999	10.15	10	1.02	2.78	Oct-July
1999-2000	14.97	10	1.50	2.78	Dec-Sep
2001-2002	20.16	14	1.44	3.89	Jan-Feb
2002	1.29	1	1.29	0.28	Sep
2005	3.02	5	0.60	1.39	June-Oct

2006	1.36	1	1.36	0.28	Dec
2009	4.09	5	0.82	1.39	Jan-May
2009	2.72	2	1.36	0.56	Nov-Dec
2014-2015	4.33	5	0.87	1.39	Oct-Feb
2019	2.14	3	0.71	0.83	April-June
2022	1.01	1	1.01	0.28	April

The drought characteristics SDI 6 at Chauk Station, summarized in the table 7 for various years. The highest severity recorded is 20.16 in 2001-2002, indicating an extreme drought event. The longest duration observed is 16 months during 1995-1996. Higher magnitudes generally indicate more intense drought conditions. The highest relative drought frequency value of 4.44 occurs in 1995-1996, indicating a high frequency of drought conditions relative to other periods.

Table 8. Drought Characteristics SDI 9 for Chauk Station

Year	Severity	Duration	Intensity	Relative drought Frequency	Start ~ End
1993-1995	30.05	28	1.07	7.78	July-Oct
1997	16.13	11	1.47	3.06	Feb-Dec
1998	1.07	1	1.07	0.28	Oct
1999-2001	43.97	27	1.63	7.50	Oct-Dec
2002	1.33	3	0.44	0.83	Sep-Nov
2005-2006	7.19	11	0.65	3.06	May-March
2009	2.23	2	1.12	0.56	Nov-Dec
2014	3.22	3	1.07	0.83	Oct-Dec
2019	1.9	6	0.32	1.67	Jan-June

The drought characteristics for SDI 9 in Chauk Station is summarized in Table 8 over varying periods. At 1993-1995 and 1999-2001, had relatively high severity and duration, suggesting prolonged and severe drought conditions during those periods. 2002 and 2019, had lower severity and duration but still experienced drought conditions.

Table 9. Drought Characteristics SDI 12 for Chauk Station

Year	Severity	Duration	Intensity	Relative drought Frequency	Start ~ End
1993-1997	55.21	54	1.02	15.00	July-Dec
1999-2001	39.56	24	1.65	6.67	Sep-Aug
2001-2002	7.6	10	0.76	2.78	Oct-July
2005-2006	6.26	13	0.48	3.61	May-May
2019	1.62	3	0.54	0.83	Oct-Dec

Table 9 highlights the characteristics of drought events at Chauk Station, measured by the Standardized Drought Index (SDI) at 12-month timescale. The most severe and prolonged drought occurred between 1993-1997, with a severity of 55.21 and a duration of 54 months. The second most notable drought spanned from 1999-2001, lasting 24 months with a severity of 39.56. The drought is shorter in duration but quite severe. Shorter droughts such as in 2001-2002 and 2005-2006, had lower severities (7.6 and 6.26 respectively) indicating mild drought conditions.

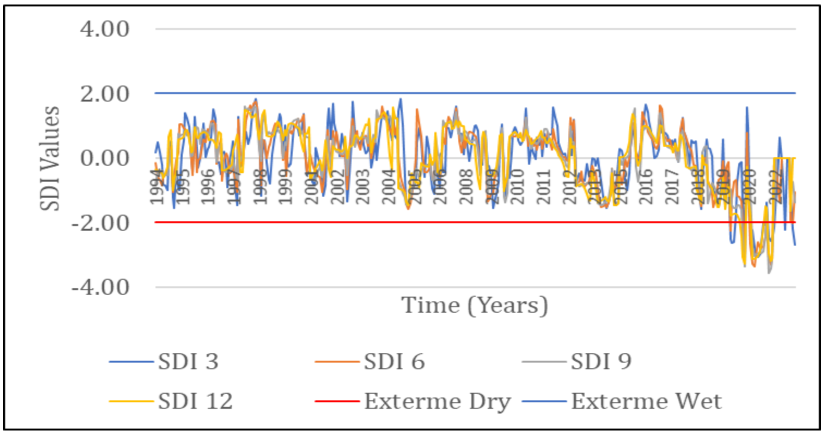

Figure 4. SDI Results for Magway Station

This figure shows the different timescales affect drought assessment, with shorter indices (SDI 3) reflecting rapid changes, while longer indices (SDI 12) provide a more comprehensive overview of climate trends over time. From figure, drought periods can be observed in 2020-2021.

Table 10. Drought Characteristics SDI 3 for Magway Station

Year	Severity	Duration	Intensity	Relative drought Frequency	Start ~ End
1994	1.08	2	0.54	0.57	July-Aug
1994-1995	5.06	5	1.01	1.44	Oct-Feb
1997	1.46	1	1.46	0.29	Sep
1998	1.16	1	1.16	0.29	Oct-Feb
2001	2.03	2	1.02	0.57	Aug-Sep
2002	1.84	2	0.92	0.57	Sep-Oct
2005	6.37	6	1.06	1.72	May-Oct
2006	1.11	1	1.11	0.29	Aug
2009	4.76	4	1.19	1.15	April-July
2009-2010	2.29	3	0.76	0.86	Nov-Jan
2014	9.03	9	1.00	2.59	April-Dec
2015	1.46	2	0.73	0.57	May-June
2018	3.22	4	0.81	1.15	Aug-Nov
2019	5.08	4	1.27	1.15	May-Aug
2019-2020	17.01	2	8.51	0.57	Oct-Sep
2021-2022	12.15	7	1.74	2.01	Sep-March
2022	3.53	2	1.77	0.57	June-July
2022	6.11	3	2.04	0.86	Oct-Dec

Above Table 10, the years 2019-2020 and 2021-2022 stand out for their severity and significant impact, highlighting increasing climate stress in recent years. The intensity of these droughts varies, with some, like those in 2019-2020, being short but extremely intense, while others, such as in 2014, are more prolonged but less intense on a monthly scale.

Table 11. Drought Characteristics SDI 6 for Magway Station

Year	Severity	Duration	Intensity	Relative drought Frequency	Start ~ End
1994	1.7	3	0.57	0.86	Oct-Dec
1997	1.06	1	1.06	0.29	Sep
2001	1.97	3	0.66	0.86	July-Sep
2005	7.34	6	1.22	1.72	April-Sep
2009	5.98	6	1.00	1.72	Jan-June
2014-2015	14.18	14	1.01	4.02	Feb-March
2018	2.89	4	0.72	1.15	Aug-Nov
2019-2020	21.38	19	1.13	5.46	March-Sep
2021-2022	14.35	8	1.79	2.30	Sep-April
2022	4.98	3	1.66	0.86	Oct-Dec

Above Table 10, the 2014-2015 drought lasted for 14 months and had a severity of 14.18. The 2019-2020 drought stands out as the most severe and extended, with a severity of 21.38 over 19 months and an intensity of 1.13. The 2021-2022 drought, although shorter than the 2019-2020 event, had a notably high intensity of 1.79.

Table 12. Drought Characteristics SDI 9 for Magway Station

Year	Severity	Duration	Intensity	Relative drought Frequency	Start ~ End
2005-2006	12.49	18	0.69	5.17	March-Aug
2009	3.9	7	0.56	2.01	Jan-July
2009	3.64	3	1.21	0.86	Oct-Dec
2014	14.85	12	1.24	3.45	Jan-Dec
2018	1.13	1	1.13	0.29	Sep
2019-2022	66.76	37	1.80	10.63	Jan-Jan
2022	1.38	1	1.38	0.29	Dec

Table 12 is the drought characteristics for Magway Station, represented by the Standardized Drought Index (SDI) at 9-month timescale. The data highlights the variability in drought characteristics over different years, with an increase in severity and duration in recent years, particularly during the 2019-2022 period.

Table 13. Drought Characteristics SDI 12 for Magway Station

Year	Severity	Duration	Intensity	Relative drought	Start ~ End

				Frequency	
2005-2006	9.25	14	0.66	4.02	April-May
2009	2.42	3	0.81	0.86	Oct-Dec
2013-2014	20.78	18	1.15	5.17	July-Dec
2018	3.61	3	1.20	0.86	July-Sep
2019-2021	65.56	33	1.99	9.48	April-Dec
2022	1.63	1	1.63	0.29	Oct

From above Table, the droughts of 2009, 2018, and 2022 were relatively short-lived and less intense, suggesting minimal impact on water resources during these periods. Overall, the data demonstrates the variability in drought characteristics, including intensity, duration, and frequency, with the 2019-2021 drought representing the most extreme hydrological event in this dataset.

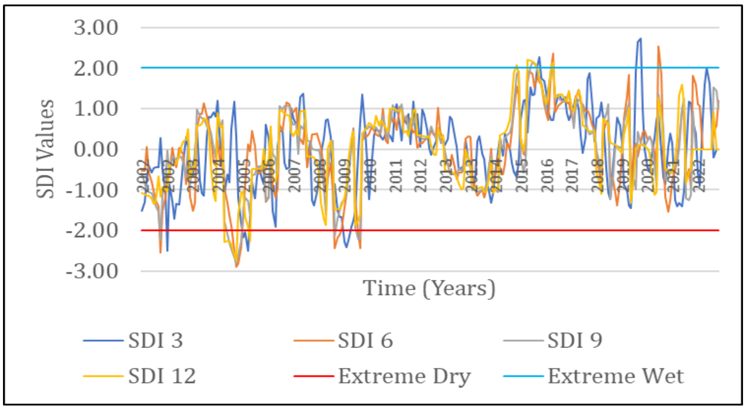

Figure 5. SDI Results for NyaungU Station

This figure illustrates the Standardized Drought Index (SDI) values across different timescales- 3, 6, 9 and 12 months plotted from 2002 to 2022. According to figure, extreme wet periods seem to occur from 2015 to 2018 and in parts of 2020. Extreme dry events are less but appear in 2002, 2005 and 2009.

Table 14. Drought Characteristics SDI 3 for NyaungU Station

Year	Severity	Duration	Intensity	Relative drought Frequency	Start ~ End
2002	5.88	8	0.74	3.19	Jan-Aug
2002-2003	11.36	9	1.26	3.59	Nov-July
2004	2.24	2	1.12	0.80	March-April
2005	2.53	3	0.84	1.20	Jan-March
2005-2006	16.24	12	1.35	4.78	July-June
2006	3.45	2	1.73	0.80	Oct-Nov
2008	4.5	5	0.90	1.99	March-July
2009	17.06	10	1.71	3.98	Feb-Nov
2010	1.45	2	0.73	0.80	April-May
2014	3.96	5	0.79	1.99	Aug-Dec
2018-2019	2.66	3	0.89	1.20	Dec-Feb
2019	3.02	3	1.01	1.20	Sep-Nov

2021	6.64	6	1.11	2.39	May-Oct

Above table, the highest drought severity was recorded in 2005-2006 (16.24) with a duration of 12 months, indicating a prolonged and extreme drought period. Another notably severe drought occurred in 2009, with a severity of 17.06 over 10 months.

Table 15. Drought Characteristics SDI 6 for NyaungU Station

Year	Severity	Duration	Intensity	Relative drought Frequency	Start ~ End
2002-2003	10.27	8	1.28	3.19	June-Jan
2003	4.03	3	1.34	1.20	Oct-Dec
2005	17.99	9	2.00	3.59	Feb-Oct
2006	5.59	6	0.93	2.39	July-Dec
2008-2009	14.9	11	1.35	4.38	Sep-July
2009	5.78	3	1.93	1.20	Oct-Dec
2014	5.85	6	0.98	2.39	March-Aug
2019	3.32	4	0.83	1.59	March-June
2021	5.5	6	0.92	2.39	Jan-June

The table provides drought characteristics for NyaungU Station, derived from the Streamflow Drought Index (SDI 6) over different years. The most critical drought periods, 2005 and 2008-2009, indicate severe hydrological stress, potentially impacting agricultural productivity, water resource availability, and the overall stability of the ecosystem.

Table 16. Drought Characteristics SDI 9 for NyaungU Station

Year	Severity	Duration	Intensity	Relative drought Frequency	Start ~ End
2002-2003	14.12	18	0.78	7.17	March-Aug
2005-2006	29.98	20	1.50	7.97	Jan-Aug
2008	2.11	2	1.06	0.80	Sep-Oct
2009	9.67	7	1.38	2.79	Jan-July
2009	6.34	3	2.11	1.20	Oct-Dec
2014	10.56	12	0.88	4.78	Jan-Dec
2019	1.91	2	0.96	0.80	Jan-Feb
2019	2.8	3	0.93	1.20	Oct-Dec
2021	3.59	3	1.20	1.20	Oct-Dec

The data from Table 16 highlights the drought characteristics at NyaungU Station with the severity, duration, intensity and relative frequency of droughts between 2002 and 2022. This hydrological event represents one of the most significant and prolonged water resources deficits, characterized by substantial water scarcity in 2005-2006 drought.

Table 17. Drought Characteristics SDI 12 for NyaungU Station

Year	Severity	Duration	Intensity	Relative	Start ~ End

				drought Frequency	
2002-2003	14.78	17	0.87	6.77	Jan-May
2004	2.38	2	1.19	0.80	Aug-Sep
2005-2006	11.97	11	1.09	4.38	July-May
2008	4.9	3	1.63	1.20	July-Sep
2009	8.16	7	1.17	2.79	Jan-July
2009	5.25	3	1.75	1.20	Oct-Dec
2013-2014	13.52	17	0.80	6.77	Aug-Dec
2018	1.1	1	1.10	0.40	Sep
2019	1.98	2	0.99	0.80	Oct-Nov
2020	2.19	2	1.10	0.80	Aug-Sep

The drought characteristics SDI 12 at NyaungU Station, as described in Table 17. The most severe drought events occurred in 2002-2003, 2005-2006 and 2013-2014, with high severity values. These extended drought periods highlight the critical impact of long-term water deficits on regional water availability and management.

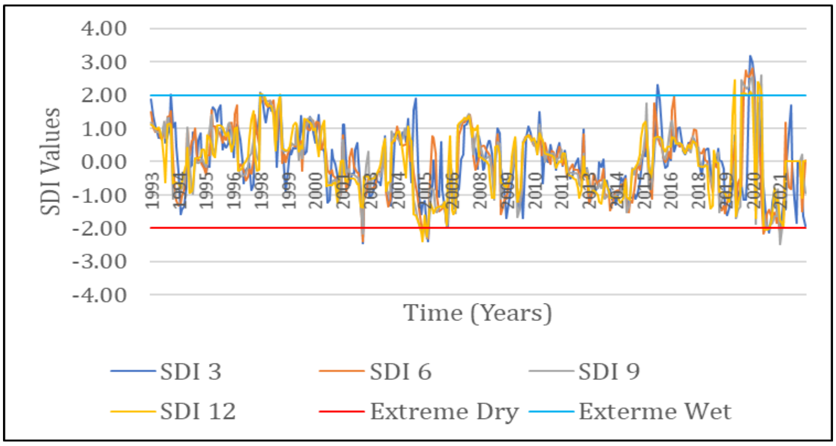

Figure 6. SDI Results for Sagaing Station

From figure, SDI values vary over time, reflecting periods of drought and wet conditions. At higher SDI timescales, there are fewer drought events, but these events tend to last longer. At Sagaing station, all SDI values drop significantly, indicating a severe drought period in 2002, 2005 and 2021.

Table 18. Drought Characteristics SDI 3 for Sagaing Station

Year	Severity	Duration	Intensity	Relative drought Frequency	Start ~ End
1994	5.15	4	1.29	1.11	May-Aug
2001	2.38	2	1.19	0.56	Feb-March
2002-2003	7.74	11	0.70	3.06	Oct-Aug
2003-2004	3.6	3	1.20	0.83	Nov-Jan
2005	11.51	8	1.44	2.22	April-Nov
2006	1.06	1	1.06	0.28	March

2006-2007	10.57	9	1.17	2.50	June-Feb
2009	5.63	6	0.94	1.67	March-Aug
2009-2010	5.2	5	1.04	1.39	Oct-Feb
2013	5.9	8	0.74	2.22	Jan-Aug
2013-2015	17.13	19	0.90	5.28	Dec-June
2019	6.34	5	1.27	1.39	April-Aug
2019-2020	7.1	7	1.01	1.94	Oct-April
2020	1.38	1	1.38	0.28	Sep
2021-2022	18.53	12	1.54	3.33	Feb-Jan
2022	2.96	2	1.48	0.56	June-July
2022	4.66	3	1.55	0.83	Oct-Dec

The analysis of drought characteristics at Sagaing Station, based on the SDI 3, is presented in Table 18. The table shows a significant variation in drought severity, with peaks occurring during 2013-2015 and 2021-2022. The most severe drought was recorded from February 2021 to January 2022, lasting 12 months with a severity value of 18.53. Another prolonged drought event spanned 19 months between 2013 and 2015, with a severity of 17.13, emphasizing the persistent risk of extended dry periods in the area. Additionally, shorter but intense droughts, such as those in 2005 and 2019, had intensities of 1.44 and 1.27, respectively.

Table 19. Drought Characteristics SDI 6 for Sagaing Station

Year	Severity	Duration	Intensity	Relative drought Frequency	Start ~ End
1994	6.77	7	0.97	1.88	Feb-Aug
2001	3.12	3	1.04	0.87	July-Sep
2002-2003	13.28	17	0.78	3.69	Aug-Dec
2005	12.32	7	1.76	3.42	April-Oct
2006-2007	14.2	12	1.18	3.94	Feb-Jan
2009	6.38	7	0.91	1.77	Jan-July
2009	3.6	3	1.20	1.00	Oct-Dec
2013-2015	24.46	29	0.84	6.79	Jan-May
2015	1.11	1	1.11	0.31	Dec
2019	8.55	8	1.07	2.38	Jan-Aug
2019	3.33	4	0.83	0.93	Oct-Jan
2020	1.46	1	1.46	0.41	Sep
2021	19.27	11	1.75	5.35	Feb-Dec
2022	2.46	2	1.23	0.68	Oct-Nov

Between 1994 and 2022, several severe drought events have been recorded in Table 19. The prolonged drought from 2013 to 2015 lasted 29 months, with a severity value of 24.46 and a moderate intensity of 0.84. This event recorded the highest relative drought frequency at 6.79, highlighting its substantial impact. Similarly, the drought from 2006 to 2007 lasted 12 months and had a severity of 14.2, coupled with a higher intensity of 1.18, indicating significant water stress.

Additionally, shorter but intense droughts, such as the seven-month drought in 2005, which had a intensity of 1.76, a severity of 12.32, and a relative frequency of 3.42.

Table 20. Drought Characteristics SDI 9 for Sagaing Station

Year	Severity	Duration	Intensity	Relative drought Frequency	Start ~ End
1994	6.14	8	0.77	2.22	Jan-Aug
2001	3.16	3	1.05	0.83	July-Sep
2002	4.5	4	1.13	1.11	Aug-Nov
2005-2006	34.17	24	1.42	6.67	Jan-Dec
2008	1.13	1	1.13	0.28	Sep
2009	4.7	7	0.67	1.94	Jan-July
2009	4.17	3	1.39	0.83	Oct-Dec
2013-2015	16.55	20	0.83	5.56	Oct-May
2019	7.52	8	0.94	2.22	Jan-Aug
2019	4.49	3	1.50	0.83	Oct-Dec
2020	1.86	1	1.86	0.28	Sep
2021-2022	22.15	13	1.70	3.61	Jan-Jan

The drought characteristics at Sagaing Station, presented in Table 20, show significant variation in both severity and duration over the years analyzed. The most intense drought occurred in 2005-2006 and 2021-2022, with severity indices of 34.17 and 22.15, respectively. The drought from 2005 to 2006 lasted 24 months, featuring a substantial intensity of 1.42 and a high relative drought frequency of 6.67, reflecting a prolonged period of severe water stress. In comparison, the 2021-2022 drought spanned 13 months but had an even higher intensity of 1.70, indicating considerable risk to water resource availability.

Table 21. Drought Characteristics SDI 12 for Sagaing Station

Year	Severity	Duration	Intensity	Relative drought Frequency	Start ~ End
2001	1.89	2	0.95	0.56	July-Aug
2002-2003	6.69	12	0.56	3.33	Aug-July
2005-2006	31.6	20	1.58	5.56	Jan-Aug
2006	4.47	3	1.49	0.83	Oct-Dec
2008	2.16	2	1.08	0.56	Aug-Sep
2009	2.9	3	0.97	0.83	Oct-Dec
2012	1.95	2	0.98	0.56	Aug-Sep
2013-2015	19.94	23	0.87	6.39	June-April
2018	2.73	2	1.37	0.56	Aug-Sep
2019	3.17	3	1.06	0.83	May-July
2019	3.83	3	1.28	0.83	Oct-Dec
2020	1.71	1	1.71	0.28	Sep
2021	12.2	8	1.53	2.22	May-Dec

2022	1.08	1	1.08	0.28	Oct

The drought characteristics at Sagaing Station, based on the SDI 12 is shown in Table 21. Over this period, droughts range from mild (such as 2001, 2020 and 2022) to severe (2005-2006 and 2013-2015). The most intense drought was observed in 2005-2006, with a severity of 31.6 lasting for 20 months, reflecting a particularly prolonged and severe drought period. Similarly, the 2013-2015 drought extended for 23 months, resulting in significant effects on local water resources.

D. Conclusion

The analysis of hydrological drought characteristics using the Streamflow Drought Index (SDI) at different timescales (3, 6, 9 and 12 months) across selected stations provide the assessment of drought behaviour and its implications on water resources over recent decades. From this research, critical drought periods, such as 2005-2006, 2013-2015 and 2019-2021 for all stations were characterized highest severity and extended duration. These extreme hydrological drought conditions emphasize the necessary for practice and strategic water resources management measures, as well as hydrological drought mitigation practices. Longer SDI timescales (SDI 9 and SDI 12) provided a more prolonged hydrological drought events, while shorter timescales (SDI 3 and SDI 6) captures more immediate, intense drought periods. The observed increase in drought frequency in recent years indicates an increasing susceptibility to hydrological extremes, likely intensified by climate variability and changing climatic conditions. Therefore, this study shows the importance of conducting targeted research on hydrological drought in Central Dry Zone, where both population density and significant investments are concentrated. This finding is essential for enhancing agricultural planning, improving early warning systems, and optimizing water resource management, ensuring sustainable development in Central Dry Zone, Myanmar.

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