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Hydrological Drought Severity in Different Return Periods in Rivers of Ardabil Province, Iran

Elnaz Ghabelnezam [1], Raoof Mostafazadeh [2,*], Zeinab Hazbavi [2] and Guangwei Huang [3]

1 Department of Rangeland and Watershed Management, Faculty of Agriculture and Natural Resources, University of Mohaghegh Ardabili, Ardabil 56199-11367, Iran
2 Water Management Research Center, Department of Rangeland and Watershed Management, Faculty of Agriculture and Natural Resources, University of Mohaghegh Ardabili, Ardabil 56199-11367, Iran
3 Graduate School of Global Environmental Studies, Sophia University, Tokyo 102-8554, Japan
* Correspondence: raoofmostafazadeh@uma.ac.ir; Tel.: +98-4531505150

Abstract: Hydrological drought (HD) characterization with different return periods is essential to appropriately design the best water management practices. In particular, characterizing the interactive relations of discharge, drought, and return periods using a novel triple diagram can deepen the interpretation of regional droughts, which have not been adequately considered, especially in semi-arid areas. Considering the critical role of HD in water exploitation and management in Iran, this study was therefore conducted to analyze the HD in different return periods in rivers of the Ardabil Province (area = 17,953 km^2). To this end, the streamflow drought index (SDI) was computed using DrinC software at 1-, 3-, and 6-month time scales for 25 hydrometric stations during 1981–2014. Then, the drought severity was evaluated by CumFreq software in different return periods (2, 5, 10, 25, 50, and 100 years). Finally, the relationship between discharge, SDI, and return periods was analyzed using triple diagram models. The results revealed that the drought events had mild ($-1 \leq \text{SDI} < 0$) and moderate ($-1.5 \leq \text{SDI} < -1$) severity for most study stations in the study area. The mean values of SDI in the 1-, 3-, and 6-month time scales were 1.08, 0.80, and 0.55, respectively. At all study time scales, the drought severity in both rivers with low and high flows increased with increasing return periods. In such a way, the maximum drought severity has been found for rivers with high flow at a 100-year return period. The current results can be considered a screening tool for the distinctive conservation and directive management of watershed resources.

Keywords: drought analysis; extreme drought; hydrological variations; water management

Citation: Ghabelnezam, E.; Mostafazadeh, R.; Hazbavi, Z.; Huang, G. Hydrological Drought Severity in Different Return Periods in Rivers of Ardabil Province, Iran. *Sustainability* **2023**, *15*, 1993. https://doi.org/10.3390/su15031993

Academic Editor: Francesco Faccini

Received: 29 December 2022
Revised: 13 January 2023
Accepted: 18 January 2023
Published: 20 January 2023

1. Introduction

During the last century, due to the mounting greenhouse gas concentration in the atmosphere and the consequent increase in global temperature, there have been significant changes in the global climate. These changes have greatly affected the hydrological cycle and available water resources, leading to severe natural disasters, such as extreme floods and droughts. Holistic characterization of water extremes showed that some Asian countries had experienced the most disastrous extreme events. For instance, the 2011 Chao Phraya River flood was the most catastrophic in Thai history, covering an area of 100,000 km^2 and causing 813 deaths across the country [1,2]. Further, in India, monsoon droughts in 1982, 1987, 2002, and 2009 adversely affected agricultural production, causing considerable economic losses. Intensification of longer and more frequent heat waves is predicted in India, which could increase heat stress and mortality rates [3]. In addition, drought in terms of environmental problems leads to insect infestation, plant and human diseases, habitat and landscape degradation, air quality and available water reduction, and increasing fire due to vegetation disturbances [4].

Since droughts, like other natural disasters, are not usually limited to a specific area and period, they are often considered the most severe natural disasters. The drought phenomenon can occur over a month, year, or several consecutive years from a temporal point of view, which often affects large areas [5–7]. However, there are several definitions of drought with different perspectives. The World Meteorological Organization (WMO) definition has been commonly accepted as a persistent and widespread lack of precipitation [8]. The UN Convention against Drought and Desertification (UNCDD) defines drought as a phenomenon that occurs naturally when rainfall is significantly lower than normal, which causes severe hydrological imbalances in the water resource production of watershed systems [9]. The Food and Agriculture Organization (FAO) also defines the drought risk as the percentage of years that crops decrease due to moisture deficiency [10]. In general, these various definitions are used for drought to analyze the frequency, severity, duration, and area of drought in a given return period.

The types of water scarcity that influence the amount of rainfall, soil moisture storage, flow, and water resources are classified into five categories: meteorological, agricultural, hydrological, socio-economic, and groundwater droughts [11,12]. Meteorological droughts initiate from a lack of rainfall and is closely related to other drought types [13]. The onset of agricultural droughts depends on the antecedent soil moisture conditions depending on the onset of meteorological droughts [11]. Hydrological (streamflow) droughts usually occur following meteorological and agricultural droughts in a sequence. A lack of rainfall over a long time also affects surface water bodies (rivers and lakes), resulting in a shortage of natural water supply [14,15]. The cascade of these three mentioned droughts eventually affects groundwater storage, resulting in a groundwater drought [16]. Lastly, socio-economic droughts occur when an imbalance between supply and demand happens. Herein, the surface and underground water scarcity affect society, supply, and demand for socio-economic goods [12,17]. The severity of impact mounts from meteorological to socio-economic droughts.

According to the literature review, hydrological drought (HD) is recognized as the most critical type of droughts, which is caused by insufficient surface or groundwater resources because of various activities, such as agricultural uses, urbanization, industrial uses, and hydropower generation. Both surface and groundwater availability and the sustainable development of human life depend on water-related activities [18]. Different studies confirmed that the increased evapotranspiration due to rising temperatures without increasing rainfall had increased the severity and frequency of HDs during the 21st century worldwide [19]. Although climatic factors are known as leading causes of drought, the role of human activities in the drought phenomenon, such as improper irrigation schemes in agriculture, over-extraction of water, land-use and land cover change, and continuous urban and industrial expansion, ultimately leads to changes in the characteristics and occurrence of HD, particularly in arid and semi-arid regions [19,20].

Given the increase in the frequency, duration, severity, and area of drought events and their effects in recent decades, drought monitoring has played a prominent role in formulating strategic plans. Various methods and techniques are used to study and monitor drought characteristics. The drought index is a fundamental tool to assess drought characteristics and effects [18]. Using an appropriate drought index, as an essential part of a drought monitoring system, is the most common approach to describe drought conditions. To this end, different research has been conducted to predict the HD using different indices, including the standardized hydrological index (SHI) [21], standardized precipitation index (SPI) [22], deficit volumes (DV) [22], standard runoff index (SRI) [23], reconnaissance drought index (RDI) [24], and streamflow drought index (SDI) [6,25]. The SDI is one of the most widely used indicators and is applied as a suitable, simple, and effective method for assessing and interpreting HD characteristics [6,25,26]. Thanks to the SDI dependency on the cumulative volume of the streamflow, the water balance of rivers could be determined, and the drought effects on the river would be characterized by the frequency and severity of the HDs.

The results of the SDI application highlighted the affectability of different parts of the world from HD in various severities. For instance, in northwestern Iran [27]; the upper

Yangtze River basin [28]; Ramganga river, India [29]; Lorestan Province, western Iran [7]; Ethiopia [30]; Yesilirmak Basin, Turkey [31]; and Jhelum Basin, NW Himalaya [32], the SDI was computed and its spatiotemporal variations were mapped. Their findings verified the existence of severe regional drought and emphasized the necessity to develop effective mitigation and resilience-based measures against future HD trends. In addition, some studies connected a nexus between HD and other types of droughts, particularly in terms of climate change signals. In this context, David and Davidová [22], using long-term data, assessed meteorological droughts and HDs in the Blanice River watershed, Czech Republic. The results of SPI, SDI, and DV analysis indicated a significant meteorological drought and HD in the summer of 2015. Prajapati et al. [33] also calculated the SPI, SDI, and Vegetation Condition Index (VCI) as the representativeness of meteorological, hydrological, and agricultural droughts, respectively. In addition, they determine the correlation between these drought indices and foodgrain production. They found a significant correlation between 3-month SPI (r = −0.72) and 5-month VCI (r = −0.81) with foodgrain production. Furthermore, Ahsan et al. [32] explored the concurrence of abrupt change points in the streamflow data with climatic variables. Consequently, they reported the effect of climate change in impacts of drought occurrence in the Jhelum Basin, NW Himalaya.

Signatures of HD have been recorded in Iran, a developing country mainly dominated by arid and semi-arid climates. For example, Koushki et al. [34] investigated the temporal relationship between meteorological drought and HD in the Karkheh Watershed. They have come to the conclusion that there is a direct and significant relationship at the 99% level between the correlation coefficient of precipitation, flow rate, and two drought indices of SPI and SDI. Moreover, in Kurdistan Province, Mortezaii et al. [35] analyzed the meteorological droughts and HDs, respectively, using the standardized precipitation evapotranspiration index (SPEI), groundwater resources index (GRI), and SDI. Their results verified a high correlation between SPEI and GRI. Additionally, they reported the influence of meteorological drought after two years or more on the ground water level. Akbari et al. [36] also investigated the hydro-climatic reasons for the drying up of the Hamon lakes on the border of Iran and Afghanistan using SDI and SPI. The main reason for the lake dryness is attributed to inappropriate water regulation in upstream, which dramatically reduces the inflow of the Hirmand River into the lakes. According to the previous studies [37–42], Ardabil Province, northwestern Iran, has experienced a decrease in autumn rainfall and, as a result, a decrease in river discharge. In addition to reduced rainfall, lack of proper water management and imbalance consumption in agriculture and drinking water have led to continued drought, which leads to groundwater depletion, base flow ceases, and the drying of some rivers. Accordingly, the accurate analysis and prediction of the drought severity phenomenon can, in turn, be of great help in managing and improving the livelihood of communities, thus reducing drought impact.

However, from the literature review, it was clarified that several kinds of research were conducted on SDI application for drought assessment, while the SDI characterization in different return periods was not considered. Incorporating the return period concept to HD is necessary for holistic planning and proper water management [21,43]. The growing attention to conserving water resource health heartens water managers and local and national organizations to use the best available tools and scientific understanding to progress or advance new executive schemes. Therefore, the current attempt is a supplementary study to the last research conducted in the study area [37,44] to comprehensively study the HD in rivers of Ardabil Province from diverse lookouts. Within this context, the current study was formulated to (1) determine the changes of HD in different time scales; (2) recognize the rate of changes in drought severity in the short and long-term return periods; and (3) investigate the interactive relations of discharge, drought severity, and return periods.

2. Materials and Methods

2.1. Study Area

Ardabil Province is located in the northwest of the Iranian plateau and between the meridians of 47°15′ and 48°56′ east longitude and 37°9′ and 39°42′ north latitude. The province has an area of 17,953 km^2, which covers about 1.09 % of the total area of Iran. The study area is bordered by East Azarbaijan Province from the west and Guilan Province from the east. The northern part of Ardabil Province is the neighbor of the Republic of Azerbaijan, and Zanjan Province is located in the south of the region (Figure 1). The diversity in climatic conditions and extensive rangelands created several rivers in the study area. The mountainous topography is one of the prominent features of the region. The climate of study area is cold semi-arid. The average value of annual precipitation ranges from 250 to 600 mm [42]. Figure 1 shows the geographical location of Ardabil Province in Iran and the selected river gauge stations used in this research.

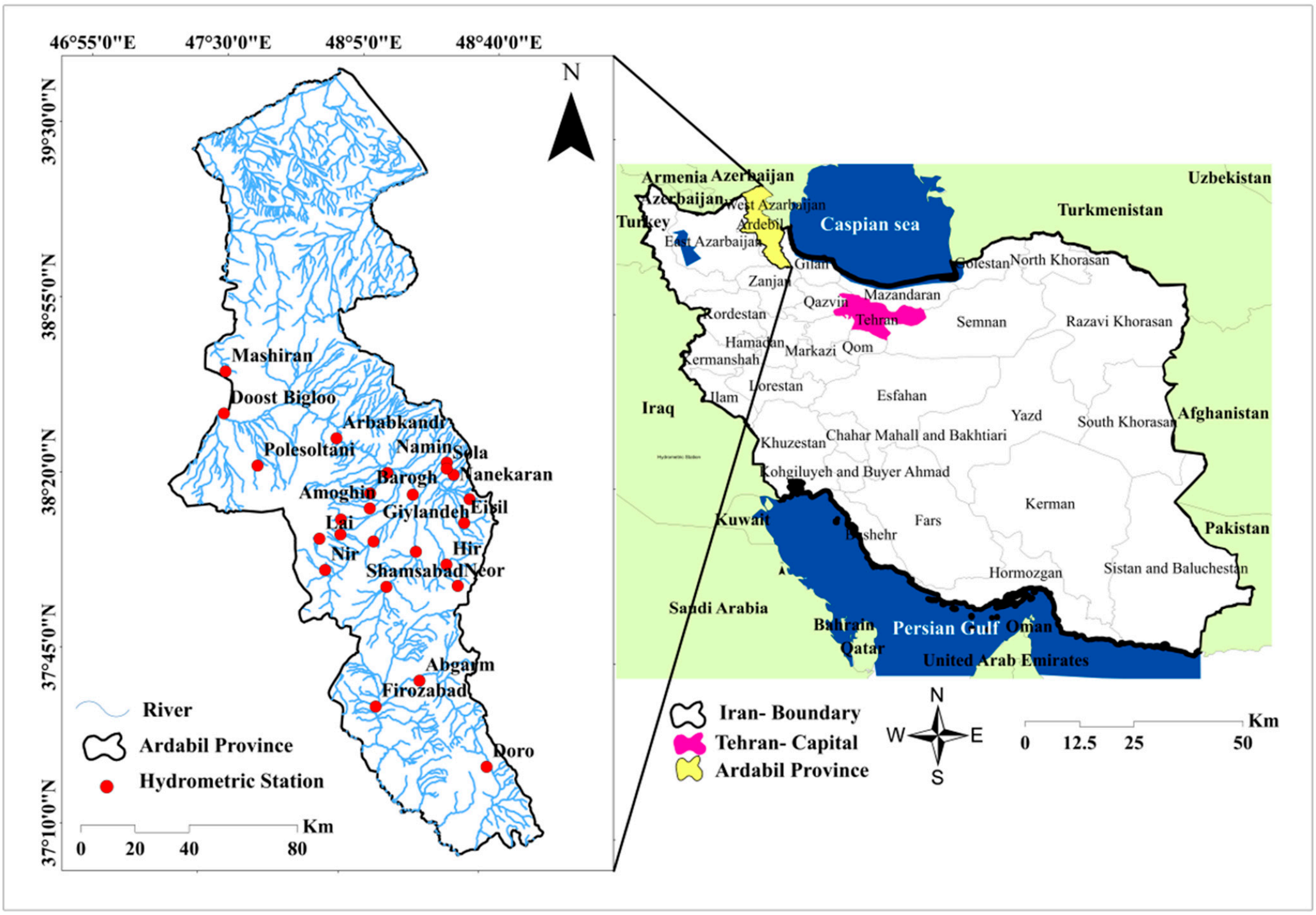

Figure 1. The geographical location of Ardabil Province and selected river gauge stations.

2.2. Methodology

2.2.1. Data Used

In the present study, daily discharge statistics of river gauge stations were used to study the characteristics of HD in Ardabil Province. For this purpose, river flow data recorded in 25 river gauge stations were collected with an available period of 33 years from 1981 to 2014 (Figure 1; Table 1). The data quality control regarding their accuracy and homogeneity was also performed by previous research, e.g., [25,42,44,45]. For instance, Mostafazadeh et al. [45] reported a significant difference between Ardabil Province watersheds in terms of river discharge. The river gauge stations located in the central region of the province have stability in discharge values, which indicates the continuation of high water flows and the occurrence of maximum discharges.

Table 1. Specifications of river gauge stations used for drought severity analysis in Ardabil Province [44,45].

County	River	Hydrometric Station	Watershed Area (km^2)	Mean Discharge (m^3/s)	Elevation (m)	Latitude	Longitude
						Degree Minute Second	
Ardabil	Noran Chay	Atashgah	44	0.115	1773	38°13′05″	48°03′23″
	Gharasou	Aladizgeh	22	0.193	1347	37°13′00″	48°35′22″
	Saghezchi Chay	Eiril	8	0.234	1375	38°13′23″	48°34′30″
	Shahrivar Chay	Barogh	96	0.165	1410	38°18′17″	48°10′06″
	Balikhloo Chay	Polealmas	1070	2.976	1440	38°09′00″	48°11′01″
	Gharasou	Samian	4004	4.938	1290	38°22′53″	48°14′48″
	Soola Chay	Sola	44	0.161	1352	38°23′14″	48°29′04″
	Agh Chay	Shamsabad	128	0.317	1493	37°59′53″	48°15′14″
	Yadibolok Chay	Amoghin	110	0.199	1385	38°15′07″	48°10′40″
	Ghori Chay	Kouzetopraghi	812.5	0.947	1394	38°07′28″	48°22′01″
	Balikhloo Chay	Gilandeh	1683	2.498	1332	38°18′26″	48°21′43″
	Lay Chay	Lai	36	0.123	2068	38°07′00″	47°54′03″
	Narges Chay	Nanekaran	40	0.083	1350	38°22′17″	48°31′32″
	Dam output	Neor	44	0.166	2499	38°00′53″	48°33′43″
	Nir Chay	Nir	256	1.205	1624	38°02′02″	47°59′38″
	Namin Chay	Namin	44	0.086	1459	38°25′45″	48°29′06″
	Viladaragh Chay	Viladaragh	94	0.072	1800	38°10′38″	48°03′19″
	Hir Chay	Hir	178	0.289	1575	38°04′55″	48°30′28″
Khalkhal	Harv Chay	Abgarm	590	2.127	1535	38°41′45″	48°44′25″
	Shahrood	Doro	158	0.650	1651	37°24′38″	48°41′48″
	Firozabad Chay	Firozabad	1515	2.956	1153	37°35′08″	48°13′35″
Meshgin Shahr	Gharasou	Arbabkandi	4800	2.271	1116	38°29′41″	48°01′58″
	Khiav Chay	Polesoltani	98	0.733	1420	38°23′56″	47°41′39″
	Gharasou	Doost Bigloo	7311	6.498	780	38°33′02″	47°32′18″
Moghan	Darehrood	Mashiran	11,267	12.602	705	38°41′10″	47°32′01″

2.2.2. Streamflow Drought Index (SDI) Calculation

The SDI has been used to analyze and quantify the severity of HD. This index was first proposed by Nalbantis [46,47] and is used to identify and evaluate HD events at different time scales. Furthermore, the wet and dry periods and the severity of the drought events can be examined. In this method, it is assumed that the time series of 1-month river flows are available as Q_{ij}, in which i is the hydrological year and j is related to each month of the given hydrological year (Equation (1)) [46].

$$V_{ik} = \sum_{j=1}^{3k} Q_{ij} \quad i = 1, 2, \ldots \quad j = 1, 2, \ldots, 12 \quad k = 1, 2, 3, 4 \tag{1}$$

where V_{ik} represents the cumulative discharge of the hydrological year, i is the time series period, and k also represents the 3-month periods. Based on the cumulative discharge of V_{ik}, the SDI based on four periods (k) of the same hydrological year (i) is defined as Equation (2).

$$SDI_{ik} = \frac{V_{ik} - V_k}{S_k} 1, 2, \ldots, \quad k = 1, 2, 3, 4, 5, 6 \tag{2}$$

where V_k and S_k are the average of the total discharge volume and the standard deviation of the cumulative flow volume for the base period K, respectively [46].

The DrinC user-friendly software (Drought Indices Calculator; http://drought-software.com/; accessed on 10 January 2023) was used to calculate the SDI. This software quantifies annual, 1-month, 3-month, and daily data series [48]. For this purpose, the average monthly discharge data was introduced as input data to DrinC software. SDI values in three time scales of 1-month, 3-months, and 6-months for all selected hydrometric stations were extracted and classified into different drought categories (Table 2).

Table 2. Classification of hydrological drought based on streamflow drought index (SDI) values [46].

State	Description	Range
1	No drought	$0 \leq$ SDI
2	Mild drought	$-1 \leq$ SDI < 0
3	Moderate drought	$-1.5 \leq$ SDI < -1
4	Severe drought	$-2 \leq$ SDI < -1.5
5	Extreme drought	SDI ≤ -2

2.2.3. Analysis of SDI in Different Return Periods

Determining the most appropriate distribution in time series is the critical step in frequency analysis. CumFreq software (https://www.waterlog.info/cumfreq.htm; accessed on 10 January 2023) was used to determine the best distribution for time series of SDI in different return periods (2, 5, 10, 25, 50, and 100 years) at three time scales (1, 3, and 6 months). This software is a single variable cumulative analysis tool with different probability distribution functions that suggests the most appropriate type of probability distribution function based on the input information. For this purpose, only the SDI less than zero (Table 1) was used for drought characterization. Hence, the absolute values of SDI data obtained from DrinC software were introduced to the CumFreq software, and different statistical distributions (e.g., Gumbel, Laplace, Logistic, Log-normal, and Weibull, etc.) were fitted, Hence, the most appropriate distribution functions were determined based on the input data. Finally, based on the most appropriate distribution function, the desired results for each return period were obtained [49,50].

2.2.4. Statistical Analysis and Mapping of Drought Events

The changes in SDI values were evaluated at different time scales over different return periods using the box-and-whisker plot. In addition, the relationship between river discharge and SDI was analyzed in different return periods using Surfer 21.1.158 software. One of the main applications of this program is drawing three-dimensional diagrams. This method can be used to prepare any variable or numerical criterion. Using the Cartesian Coordinate System, it is possible to visualize variables in three dimensions through maps with similar value lines based on the Kriging interpolation method [51]. Triple diagram models indicate the internal relationship of factors affecting the drought components at the plot scale. They help to make understandings despite extremely scattered measurements. In this research, a series of contour maps are structured using the geostatistical approach to interpolate discharge and SDI values. Geostatistical applications describe the behavior of a natural occurrence considering affecting variables. Establishing an accurate variogram model is necessary to interpret and describe the fundamental relationships of a natural phenomenon. Mainly, the variogram model serves as a tool to interpret the behavior of a random field [52].

For drawing the triple diagram models and representing the value distribution, the return period and river discharge were considered independent variables, and the third variable, that is, absolute SDI values, was used as the dependent variable. The accuracy of this method has already been confirmed in the literature [51,53]. Triple diagram models can assist the understanding of the variation between scattered points, defined by the following Equation (3) [54].

$$\gamma(d) = \frac{1}{2N(d)} \sum_{i=1}^{N(d)} [C(x+d) - C(x)]^2 \quad (3)$$

where $\gamma(d)$ is the semi-variogram function; $N(d)$ is the pairs of variables for distance d; $C(x)$ is the value of the given variable; and $C(x+d)$ is the value of the random variable away from the $C(x)$ by a distance d. Defining the best-fitted semi-variogram and predicting unknown values using the Kriging are the main steps of a geostatistical assessment. Minimizing the error variance is the fundamental procedure of the Kriging approach [55,56].

The following equation can be used for the runoff and sediment values at any point of the contour map (Equation (4)).

$$C(x_0) = \sum_{i=1}^{N} w_i C(x_i) \quad (4)$$

where $C(x_0)$ is the value of the runoff and sediment values at any prediction point (x_0); $C(x_i)$ is the runoff and sediment values measurements at point i; and w_i is the weight that can be estimated using the semi-variogram function. The interpolation weights applied to data points during the grid node calculations are direct functions of the variogram model.

3. Results

3.1. Analysis of Streamflow Drought Index (SDI)

The results of SDI classification for each time scale of 1, 3, and 6 months were presented in Table 3. Based on the average values of absolute SDI results (Table 3), a 1-month drought in Doro, Gilandeh, Kouzetopraghi, Neor, Shamsabad, and Samian stations indicates mild drought; and Abgarm, Amoghin, Arbabkandi, Atashgah, Barogh, Doost Bigloo, Firozabad, Hir, Eiril, Lai, Mashiran, Namin, Nanekaran, Nir, Polealmas, Polesoltani, Sola, and Viladaragh had a moderate drought. There was also a severe drought at Aladizgeh Station (Table 3).

Table 3. SDI values of 1, 3, and 6 months in selected river gauge stations.

Station	SDI 1-Month		SDI 3-Month		SDI 6-Month	
	Maximum	Average	Maximum	Average	Maximum	Average
Abgarm	−1.97	−1.13	−1.78	−0.91	−1.39	−0.70
Aladizgeh	−2.45	−1.55	−2.06	−1.10	−2.11	−0.70
Amoghin	−2.15	−1.31	−2.54	−0.90	−1.56	−0.66
Arbabkandi	−1.79	−1.09	−1.76	−0.88	−1.52	−0.65
Atashgah	−2.12	−1.27	−1.61	−1.01	−1.49	−0.73
Barogh	−2.66	−1.17	−2.39	−1.06	−2.01	−0.73
Doro	−2.33	−0.99	−2.33	−0.75	−2.24	−0.60
Doost Bigloo	−2.20	−1.09	−2.16	−0.81	−1.99	−0.48
Firozabad	−2.21	−1.29	−1.68	−0.86	−1.60	−0.62
Gilandeh	−1.88	−0.63	−1.88	−0.45	−2.12	−0.38
Hir	−3.00	−1.22	−3.04	−0.87	−2.57	−0.57
Eiril	−3.66	−1.22	−3.71	−1.03	−1.65	−0.69
Kouzetopraghi	−1.89	−0.81	−1.92	−0.66	−1.46	−0.46
Lai	−2.48	−1.01	−2.52	−0.80	−1.83	−0.58
Mashiran	−2.99	−1.14	−2.24	−0.78	−1.86	−0.51
Namin	−1.79	−1.05	−1.81	−0.91	−1.57	−0.63
Nanekaran	−2.59	−1.17	−2.36	−0.81	−1.76	−0.60
Nir	−3.56	−1.29	−3.00	−0.92	−2.03	−0.58
Polealmas	−2.94	−1.08	−2.96	−0.79	−2.54	−0.53
Polesoltani	−2.93	−1.11	−2.54	−0.78	−3.54	−0.44
Neor	−1.91	−0.78	−2.30	−0.64	−3.81	−0.39
Shamsabad	−2.41	−0.92	−2.33	−0.68	−1.87	−0.51
Samian	−2.30	−0.94	−2.12	−0.61	−2.07	−0.44
Sola	−2.06	−1.10	−1.65	−0.84	−1.56	−0.58
Viladaragh	−3.13	−1.37	−2.37	−0.88	−1.35	−0.56

On the 3-month scale, Abgarm, Amoghin, Arbabkandi, Doro, Doost Bigloo, Firozabad, Gilandeh, Hir, Kouzetopraghi, Lai, Mashiran, Namin, Nanekaran, Nir, Polealmas, Polesoltani, Neor, Shamsabad, Samian, Sola, and Viladaragh stations had a mild drought. The moderate class of drought was characterized at Aladizgeh, Atashgah, Barogh, and Eiril stations. On a 6-month scale, drought is a mild condition in all stations. According to the calculations made based on the available data period, it could be concluded that on 1-and

3-month time scales, the highest drought severity was related to Aladizgeh Station, and on the 6-month scale was related to Atashgah and Barogh stations.

3.2. Analysis of SDI in Different Return Periods

Table 4 presents the most appropriate distributions for the three study time scales for all river gauge stations. By determining the type of distribution, the absolute SDI results for the considered return periods (2, 5, 10, 25, 50, and 100 years) were also calculated in the three temporal time scales. Figure 2 also shows the different levels of absolute SDI at different return periods on 1-, 3-, and 6-month time scales. These results verified that the drought severity has increased over time in almost all stations in the study area.

Table 4. The most appropriate type of distribution in each station for different time scales.

Stations	Time Scale		
	1-Month	**3-Month**	**6-Month**
Abgarm	Fisher–Tippett Type III	Poisson-Type	Generalized Laplace
Aladizgeh	Cauchy	Mirrored Gumbel	Laplace
Amoghin	Kumaraswamy	Laplace	Poisson
Arbabkandi	Square-Normal	Gumbel	Laplace
Atashgah	Laplace	Cauchy	Composite Laplace
Barogh	Laplace	Fisher–Tippett 2	Poisson
Doro	Generalized Laplace	Generalized Gumbel	Generalized Extreme Value (GEV)
Doost Bigloo	Mirrored Fisher–Tippett Type III	Generalized Mirrored Poisson	Composite Laplace
Firozabad	Generalized Mirrored Poisson	Mirrored Generalized Gumbel	Generalized Mirrored Poisson
Gilandeh	Root-Normal	Generalized Laplace	Log-Normal Optimized
Hir	Fisher–Tippett 2	Generalized Laplace	Root-Normal
Eiril	Fisher–Tippett 2	Fisher–Tippett 2	Generalized Mirrored Poisson
Kouzetopraghi	Generalized Laplace	Generalized Mirrored Poisson	Generalized Laplace
Lai	Generalized Extreme Value (GEV)	Mirrored Generalized Gumbel	Generalized Mirrored Poisson
Mashiran	Mirrored Frechet Type	Generalized Laplace	Root-Normal
Namin	Generalized Mirrored Poisson	Generalized Mirrored Poisson	Generalized Mirrored Poisson
Nanekaran	Generalized Laplace	Generalized Laplace	Generalized Mirrored Poisson
Nir	Generalized Laplace	Optimized Normal	Mirrored Generalized Gumbel
Polealmas	Generalized Mirrored Poisson	Generalized Gumbel	Composite Laplace
Polesoltani	Optimized Normal	Mirrored Generalized Gumbel	Generalized Laplace
Neor	Poisson-Type	Mirrored Generalized Gumbel	Generalized Laplace
Shamsabad	Generalized Laplace	Generalized Mirrored Poisson	Poisson-Type
Samian	Mirrored Generalized Gumbel	Generalized Mirrored Poisson	Generalized Laplace
Sola	Generalized Gumbel	Generalized mirrored Poisson	Generalized Mirrored Poisson
Viladaragh	Composite Laplace	Generalized Laplace	Generalized Mirrored Poisson

The minimum SDI value was found in the 2-year return period with a value of 0.4. The maximum 1-month SDI value was also obtained for the 100-year return period with a value of 10.38. The relationship between 3-month absolute SDI in different return periods showed that the severity of 3-month SDI also increases with increasing return period, with the difference that the severity of 3-month absolute SDI was lower than the 1-month SDI absolute values (Figure 2). This is because the minimum SDI in the 3-month time scale in the 2-year return period was 0.011, and its maximum was 6.55 in the 100-year return period. The severity of absolute 6-month SDI values increased with an increasing return period (Figure 2). The minimum value in the 2-year return period was 0.003, and the maximum value of SDI (SDI = 8.94) was found in the 100-year return period.

By estimating SDI in the return periods, it was found that in the 100-year return period, the drought severity in the 1-month time scale at Aladizgeh Station has a maximum value of 10.38, and the minimum value is 1.74 at Namin Station. As well, in the 3-month time scale in the 100-year return period, Eiril Station has a maximum drought severity equal to 6.55, and Sola Station has a minimum value equal to 1.74. On the other hand, in the 6-month time scale, the minimum and maximum values are equal to 8.94 and 1.55 in Neor and Viladaragh stations, respectively. It should be noted that, compared to other stations in 1- and 3- time scales, Eiril Station has the highest number of maximum droughts in the return periods. The minimum and maximum drought severity in the 1-, 3-, and 6- month time scales in the study return periods at the station level are presented in Table 5.

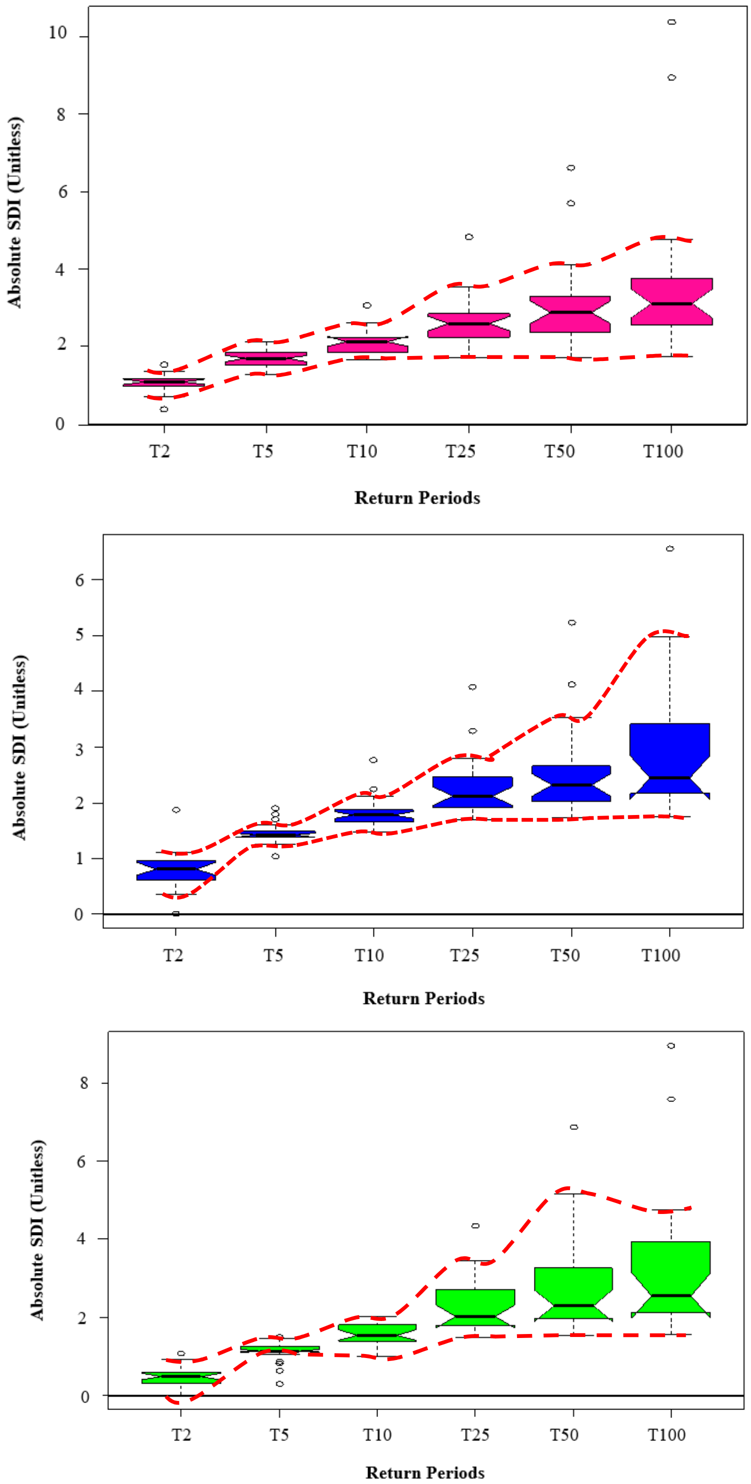

Figure 2. Box plot of the relationship between different return periods and absolute SDI at time scales of 1-month (**up**), 3-months (**moderate**), and 6-months (**down**) in all the study rivers of Ardabil Province. Dash lines represent the upper and lower confidence limits.

Table 5. Minimum and maximum absolute SDI at study stations for each study return period.

Return Period	1-Month		3-Month		6-Month	
	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum
2	1.54	0.39	1.87	0.01	1.07	0.003
	Aladizgeh	Gilandeh	Aladizgeh	Gilandeh	Neor	Polesoltani
5	2.13	1.27	1.89	1.04	1.48	0.28
	Polealmas	Gilandeh	Eiril	Gilandeh	Barogh	Gilandeh
10	3.05	1.65	2.76	1.46	2.02	1.00
	Eiril	Namin	Eiril	Atashgah	Aladizgeh	Gilandeh
25	4.82	1.71	4.08	1.70	4.33	1.48
	Eiril	Namin	Eiril	Sola	Neor	Viladaragh
50	6.62	1.73	5.23	1.73	6.86	1.53
	Eiril	Namin	Eiril	Sola	Neor	Viladaragh
100	10.38	1.74	6.55	1.74	8.94	1.55
	Aladizgeh	Namin	Eiril	Sola	Neor	Viladaragh

3.3. Results of Statistical Analysis and Mapping

The triple diagram models related to the relationship between river discharge and absolute SDI for the three study time scales in different return periods are presented in Figure 3. In these diagrams, the horizontal and vertical axes represent the return period and average discharge values, respectively. In addition, the iso-lines show the absolute SDI, in which bold blue and light blue are respectively associated with low and high drought severities.

Analysis of the 3D diagram on a 1-month time scale (Figure 3) suggests that drought severity increases with an increasing return period. However, the drought persistence decreases with an increasing return period. At this time scale, the drought severity during the return period of fewer than 10 years in rivers with low and high discharge is relatively the same. However, drought has intensified in rivers with lower discharge in the return period of more than 20 years. In the 3-month time scale diagram (Figure 3), rivers with low and high discharge in the 5-year return period have almost less drought severity and more continuity. In this time scale, in contrast to the 1-month time scale, drought severity fluctuations decrease from the return period of more than 25 years, and the drought severity in the 50- and 100-year return periods in rivers with low discharge is higher than 1-month SDI. According to Figure 3, in the 6-month time scale, the drought severity in the return period with less than 5 years in rivers with low and high discharge values is low. However, drought persistence in the 6-month SDI is longer than the other 2-time scales (i.e., 1- and 3-months). It is important to note that in rivers with high discharges, the drought severity intensifies on a 6-month scale with a return period of more than 50 years.

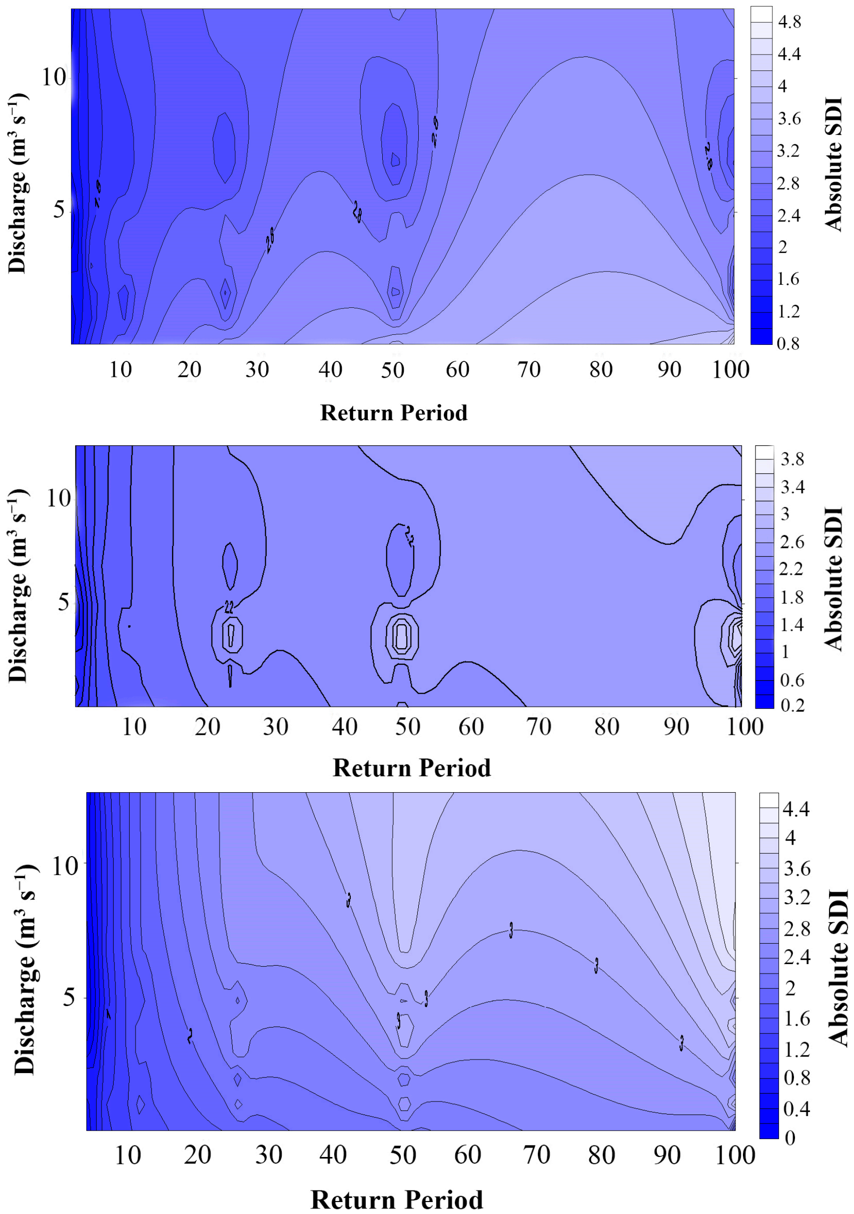

Figure 3. 3D diagram indicating the relationship between river discharges (m^3 s^{-1}), absolute SDI, and return periods at time scales of 1-month (**up**), 3-months (**middle**), and 6-months (**down**) in all the study rivers of Ardabil Province.

4. Discussion

Assessing HD through a point or site drought indicator of SDI provides critical and applied information about the rivers' spatio-temporal variation [30,31]. However, due to the significant variation in the influential factors of HD, it is still an element of debate in the field of water resource risk research. There is a tendency to monitor the regional and global drought induced by particular hydrological hazards (e.g., [7,27–32]).

The results of SDI calculation in the period of 1981 to 2014 (Table 3) showed that the severity and rate of occurrence of droughts had varied spatially over the decades. Drought events seem to have recurred in some places after a while. About 24, 72, and 4 % of the river gauge stations experienced mild, moderate, and severe HD at a 1-month time scale, respectively. In addition, 84 and 16 % of the river gauge stations are characterized by mild and moderate HD at a 3-month time scale. Finally, all river gauge stations had mild HD at a 6-month time scale. One-month drought values indicate short-term drought in selected stations, but the drought severity at the one-month scale was higher than other time scales.

In this respect, Tabari et al. [27] found significant differences in SDI of the first 3-month period (October–December), first semester (October–March), 6-month period (October–March), and 9-month period (October–June) during 1975–2009. Jahangir and Yarahmadi [7] also showed that all the study stations in Lorestan Province (Iran) had experienced at least one severe drought based on the SDI application for different time scales of 3, 6, 9, and 12 months.

The results of drought analysis in different return periods showed that the drought severity increases with the increase of the return periods. By comparing box plots, it was concluded that the 3-month SDI had a relative increase compared to the other two time scales, with an increasing return period.

The relationship between 1-month SPI and flow discharge values showed that most drought events occurred in small rivers having low discharge values. Meanwhile, the values above the median in the 3- and 6-month SDI diagrams increased with the escalation of the return period compared to 1-month SDI values. In addition, the results of the triple diagram models indicated an increase in drought severity in rivers with high discharge values in the return period of more than 50 years. In general, it can be concluded that the drought occurred in rivers with low and high discharge values. It should be noted that several factors can affect the variability of river flow regimes, some of which are natural fluctuations such as changes in rainfall and temperature. Human effects (e.g., dam effects, water diversion, and withdrawal) also cause changes in the river flow regime, which can cause uncertainty in the determination of droughts and the interpretation of results, as already reported by [36,46,47,57]. It should be noted that the selected rivers in the study area cover a wide range of different conditions, which can help in a more comprehensive interpretation of drought occurrence in different return periods.

These days, the decrease in rainfall of Ardabil Province and the continuation of drought, in addition to causing many problems for farmers, have also progressed to the limit of people's drinking water. In many villages, there is a problem with the water supply, and its quality in urban areas has decreased. Therefore, currently, if water and drought management will not be a priority of the government and private sectors, the water crisis impacts will be intensified in the near future and will confront society with pressing living conditions. A similar conclusion was demonstrated by Parchami et al. [44] and Amini et al. [25,37], who reported a mild HD throughout the hydrometric stations of Ardabil Province.

According to the results, the best-fitted distribution for the 1-month time scale was the Generalized Laplace Distribution. The Laplace distribution is attributed to the first law of Laplace errors. This distribution is used in hydrological time series to express events with high quantities. At the 3- and 6-month time scales, the best-fitted distribution was the generalized mirrored Poisson distribution. This is a discrete probability distribution that describes the probability that an event will occur at a certain number at a given time or place, provided that these events occurred at a specific and independent mean value since the last incident. In this regard, Sharma and Panu [21] introduced the Pearson three probability distribution as a proper distribution for reciting the return period characteristics for drought lengths characterized using the standardized hydrological index (SHI) series for five rivers in the Canadian prairies.

Several uncertainties could affect the obtained results concerning sampling uncertainty, missing data, and the absence of uniform standards for collecting raw data. Since the study time period in the present research was from 1981–2014, consequently, it is expected that the results will vary for different time period lengths, as also concluded by Hong et al. [28] in their HD assessment for the upper Yangtze River basin, China. Completely accurately predicting HD is not easily possible due to governing uncertainties on representative proxy variables because there is discharge as the primary input to compute HD as a natural phenomenon, which varies from place to place and time to time. Nonetheless, such uncertainties might be assessed on the basis of probabilistic methods like frequency distributions analysis leading to predict drought severity with different return periods [7].

Field observations that have been performed randomly in recent years (2015–2022) verified the occurrence of drought in most of the study rivers. Its impacts are significantly shown in the reduction of river flow and the disturbance of river ecosystems. In addition, the recorded data of water flow in river gauge stations have also confirmed this statement. It should be noted that the findings of the present study are consistent with the results of Amini et al. [37], who comprehensively assessed the severity, duration, and frequency of HD in Ardabil Province rivers.

The proposed methodology in this study is applicable to other areas worldwide, especially in arid and semi-arid regions. In addition, the current study should enable stakeholders, policymakers, and water resource managers to undertake strategic drought monitoring, prediction, modeling, and disaster risk reduction. Moreover, the obtained results are applicable for formulating regional and national programs for engendering technologies and assisting decision makers in countering drought.

5. Management Implications and Future Perspectives

In the complicated period of the Anthropocene, the negative impacts of HD on human development and sustainability are no longer just about water; they link to climate change, ecological conditions, economic trade, and resource consumption. To this end, today, water managers need to consider cross-sectoral implications and green–blue water interactions [58]. The obtained results for the interactive relationship between discharge, drought, and return periods provided by the novel presentation of triple diagram models draw strong background and roadmaps for designing drought early warning signals.

The framework outlined in the current research provides a context for studies of provincial- and national-level drought analysis. In addition, the obtained results help the experts and managers to understand the national vulnerability against HD, which would be most beneficial when the generic adaptive capacity is also concerned. Such drought analysis may be broken down by county, district, city, individual river station, or population group since the significance of a particular hazard (here, i.e., drought) will vary across the above-mentioned sections in terms of geographic location, climate condition, resource requirements, and livelihoods. This finding also has implications for comparing studies concerning the benefits of nature-based solutions to mitigate drought in semi-arid areas. This allows us to scrutinize drought dynamics from certain managerial scenarios [43].

Although the recent events related to drought have required advanced awareness, drought has not been given much attention in the research of natural hazards such as storms and floods, which have a direct impact on human life and property. Most countries currently address drought risk through reactive approaches and crisis management. Today, it is recommended to periodically forecast drought before and even after the implementation of mitigation or adaptive management program. It should be noted that the drought program is a process, not a discrete event. Accordingly, it needs to be continuously monitored and reviewed. The final goal of the drought risk assessment process is to identify sectors, population groups, or areas that are more exposed to drought and take appropriate measures to reduce its possible effects. Considering that the effective and timely monitoring of drought is the first step in reducing the damages of drought and can lead to the development of early warning systems, therefore, the current research results can help to identify the necessary measures to adjust the drought based on which the short-term and long-term effects of drought is reduced. In addition, relevant organizations should be mobilized for the development and implementation of measures. In a proactive approach, early warning systems are important because they play an essential role in integrated drought assessment, communication, and support systems. An overview of international drought early warning systems shows that effective early warning requires multi-sectoral and interdisciplinary collaboration between all relevant actors at each stage of the warning process, from monitoring to the response. Therefore, providing the necessary measures to deal with the harmful effects of drought should be considered in all management fields.

This paper did not investigate the linkage between climate change and HD, which is proposed for future research. Furthermore, it should be focused on future climate change impacts on the HD, particularly in scarcely gauged regions of Ardabil Province. The same issues could be considered for other types of drought at different spatial and temporal scales. Additionally, predicting the future regional trend of HD, in line with the requirements of sustainable development goals (SDGs), accompanies this regional HD assessment. Since the occurrence of drought can be caused by changes in climatic factors or land use change and human interventions, analyzing the separate and integrated impact of these factors is recommended in future works. Investigating the anthropogenic activities' impacts in intensifying the drought in Ardabil Province should be considered an important research subject. Comparing the degree of disturbance of the river flow and the characteristics of the flow regime of different rivers and its relationship with drought occurrence can be recommended for future studies as a supplementary analysis of results presented in the current research.

6. Conclusions

Hydrological drought (HD) analysis is more complicated than other types of droughts because this type of drought results from nonlinear interactions between climatic, hydrologic, ecologic, and anthropogenic variables. HDs may have similar frequencies or durations in a specific region. However, due to the disruption of other hydrological processes by human interventions, drought events may vary in severity and area. Examining the values of SDI showed that drought in all study river gauge stations of Ardabil Province, Iran, occurred in all three study time scales (1, 3, and 6 months), and the severity of these drought events from 1981 to 2014 had an increasing trend. The results show that in the available period, on a 1-month time scale, about 24 % of selected river gauge stations have mild drought (SDI = 0.69), 72 % have moderate drought (SDI = 1.16), and 4 % have severe drought (SDI = 1.55) conditions. On a 3-month scale, about 84 % of the selected stations had a mild drought and 16 % had a moderate drought. Mild drought events had occurred in all river gauge stations on a 6-month scale.

Currently, the number of HD events is high in rivers with low discharge. As a result, more damaging and harmful environmental effects will be expected in rivers with low discharge values. Drought management should be considered in managerial plans and policies in the context of the risk management approach to sound management of drought consequences. The emphasis of drought risk planning and adaptation should be based on the early warning of drought occurrence, and the necessary preparation should be taken to deal with drought consequences. Therefore, it is necessary to take immediate measures for proper water management in the watersheds of Ardabil Province to prevent the severe and damaging effects of HD.

Author Contributions: Conceptualization, E.G. and R.M.; methodology, E.G. and R.M.; software, E.G. and R.M.; validation, E.G., R.M. and Z.H.; formal analysis, E.G., R.M. and Z.H.; investigation, E.G., R.M. and Z.H.; resources, E.G., R.M. and Z.H.; data curation, E.G. and R.M.; writing—original draft preparation, E.G., R.M. and Z.H.; writing—review and editing, E.G., R.M., Z.H. and G.H.; visualization, E.G., R.M. and Z.H.; supervision, R.M. and Z.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Available upon request.

Acknowledgments: This work was supported by the University of Mohaghegh Ardabili, Iran.

Conflicts of Interest: The authors declare no conflict of interest.

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