

RESEARCH ARTICLE

Evaluation of hydro-meteorological drought indices for characterizing historical and future droughts and their impact on groundwater

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Abstract: The effect of meteorological and hydrological droughts is very important in arid and semi-arid regions. Analyzing these effects on groundwater supplies plays an important role for water management in those regions. This paper aims to characterize droughts in the Isfahan-Borkhar basin, an arid area of Iran. The observed hydro-climatic data (for the period of 1971-2005) were used for hydro-meteorological projections (for the period of 2006-2040). Meteorological and surface hydrological drought evaluated by Standardized Precipitation Index (SPI), Standardized Runoff Index (SRI), and the effect of hydro-meteorological droughts on groundwater was investigated by Groundwater Resources Index (GRI). Results showed that dry and wet conditions would occur in the region in the initial and subsequent decades, based on the three indices. There was a significant association between SPI, SRI, and GRI at the time scale of 12 months. The SPI estimated using only meteorological variables alone and it is useful for estimating meteorological drought forecasts. However, SRI and GRI can represent hydrological drought that computed using catchment discharge, soil moisture and groundwater level. Results showed a considerable alteration in time of drought outlines across the area and association between the variables of predicted precipitation, temperature and the kind of indices. The projection of all three drought indices indicated drier conditions in the future period (2006-2042). The results provide reasonable management strategy for management of water resources in arid coastal plains.

Keywords: climate change, SPI, SRI, GRI, drought indices, drought projection

1 Introduction

Some major climate variables, including total surface air temperature and rainfall, determine climate change.^[1] According to Global Climate Model (GCM) projections, in the future the Earth is anticipated to be warmer. The increasing rate of evapotranspiration leads to an imbalance of water in the atmosphere and surface water.^[2] Hence, researches on the effect of universal climate alteration on several segments (agriculture, water resources organization, and ecosystems) are significant for economic and social reasons. Alterations in rainfall and temperature may influence drought and flood occurrences directly^[3] and consequently have serious impacts on humans, infrastructure, and environment. Agha-Kouchak *et al.* (2015)^[3] classified droughts into several groups: meteorological,

hydrological, agricultural, and socioeconomic. Meteorological, hydrological, agricultural droughts are established on physical characteristics and climate variables. However, the socio-economic drought is related to the deficit of water resources that can happen via socioeconomic parameters.^[4] The meteorological, hydrological, agricultural droughts are based on the same concept; a drought can determine as a prolonged episode of unusual arid weather, adequately extended for the absence of water that causes significant imbalance in hydrologic cycle (*i.e.*, rainfall scarcity, soil moisture scarcity, declining level of water, deficit in water resources, and so on) for the distressed region and is produced principally through the deficiency of rainfall and increase of air temperature (high evapotranspiration), and reduction of level of soil moisture for a long time.^[5] Besides global warming, both precipitation and evapotranspiration can be predicted to alter at several scales worldwide in the future. Numerous researchers have studied historical drought characteristics,^[6,7] the association among the condition of atmosphere and the incidence of meteorological drought and drought alterations in the future by climate forecast models. Researches indicate that the standardized precipitation index (SPI), the relative precipitation index

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(RPI), the climatic water balance (CWB), and the effective drought index (EDI), can be used for the characterization of historical droughts and the assessment of future droughts.^[8–11] The SPI is a convenience method that has been applied extensively for meteorological droughts because of its simplicity and availability of needed data. Also, a prolonged meteorological drought can create a hydrological drought^[12,13] which can be analyzed using SRI. However, hydrological drought related to groundwater and how meteorological and surface-water hydrological droughts expand to create hydrological drought related to groundwater have received relatively little attention.^[14] Thus, SPI can be applied to evaluate the effect of precipitation on meteorological drought and SRI to evaluate the effect of surface hydrologic dynamics on hydrologic drought.^[15,16] Drought indices, including rainfall, air temperature, evapotranspiration, and flow in the expression (like SPI, SRI and GRI) can be desirable with future climate scenarios. These indices are necessary for evaluating drought in association with various hydrological systems, and for distinguishing amongst drought types. The SPI, SRI and GRI indices were applied in this study for evaluating the effect of climate change on drought characteristics.^[17,18] The objectives of this paper therefore were: (1) to contrast SPI, SRI and GRI indices in their capability to define chronological drought, entailing the conversion of meteorological drought to hydrological drought (both surface and groundwater drought) and (2) to examine how drought can be anticipated to change in the future, with the application of SPI, SRI, and GRI drought indices and climate projections (CMIP5 under the different scenario of RCPs) for Borkhar basin in Iran. These objectives are novel with regard to the application of data from “Climate Explorer” in Iran and the improvement and contrast of SPI, SRI and GRI projections into the future time period in the basin. The previous studies did not use and modeled the three drought indices for future time period with new climate change model and new model of downscaling with new model of climate scenario and compared them and so this study fills these gaps. Therefore the novelty of this paper includes:

1) New climate model of CMIP5 which used new statistical downscaling model under different scenarios of RCPs is applied to model future climate parameters; 2) Using new drought indices for surface and groundwater to estimate hydrological drought in the basin; 3) in order to estimate surface drought, all the climatic parameters include precipitation, temperature, evapotranspiration, humidity, sunshine hours are involved to estimate runoff and surface hydrological drought; and 4) new GMS model is used to estimate future groundwater level and calculated groundwater drought. The study region and hydro-

climatic features of the basin and data are discussed in the following section. Also, the applied drought indices SPI, SRI and GRI are presented in section 2. In the following section, drought forecasts applying GCM climate models are explained. The outcomes and the key findings are concluded in the section of results and discussion.

2 Materials and methods

The physical conditions along with hydro climatological and geology-land features of the catchment are explained first and then data and methods of calculating drought indices are described.

2.1 Study area

The Isfahan-Borkhar plain is situated in the Isfahan province of Iran. [Figure 1](#) shows the study area. This region is located between 51° 05' and 51° 58' longitude and 32° 33' and 33° 16' latitude and its area is approximately 1643 km². The general elevation of the Isfahan-Borkhar plain varies from 1731 to 1554 m higher than mean sea level. The Zayandeh-Rud River is a major river in the basin, which crosses through the south of this plain. The average temperature is approximately 16°C. The coldest month is January, and the warmest month is March. The mean annual precipitation is approximately 115 mm. The average annual potential evapotranspiration is approximately 2400 mm in the study area ([Figure 1](#)). The unconfined aquifer of Isfahan-Borkhar basin is placed in the Isfahan province of Iran.^[19] Based on the structure-sedimental zoning of Iran, the Isfahan-Borkhar basin is placed in the Sanandaj-Sirjan sub-zone in the central region of Iran. About 64% of this area (2405 km²) contains alluvial plains and the remainder 36% (1367 km²) is approximately rocky outcrops. The lithology of the rocky outcrops contains a sequence of sedimentary foundations which include permeable rocks like limestone and dolomites (*e.g.* K1sol, OMql, and Pj units), impermeable to low permeability rocks, such as shale and marl (*e.g.* Kdzsh, Ksml, and Mur units), and also sandstone and conglomerate rocks (*e.g.* TRn and K1c units). Quaternary alluvium contains soft alluvial zones and flood plain deposits comprising fine-grained soils (Qal). [Figure 2](#) displays the geological map of the Isfahan-Borkhar basin.^[20]

2.2 Climate data of future time period

Future climate data of this paper were simulated for measuring and analysing different drought indices. For this work, the data sets were obtained from the Koninklijk Netherlands Meteorologisch Institute (KNMI) which

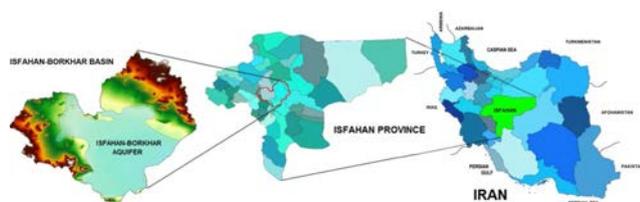


Figure 1. Overall situation of the Isfahan-Borkhar plain and its aquifer

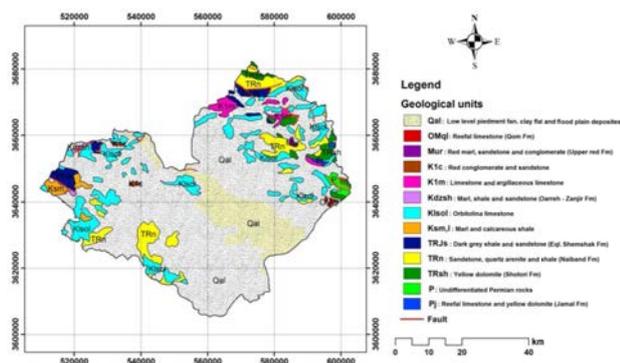


Figure 2. Geological map of the Isfahan-Borkhar basin (scale 1:100,000)

collaborated with observer station data to simulate the climate models of historical and future periods for Iran and the study region. Monthly precipitation (mm /day), the observational surface temperature ($^{\circ}\text{C}$), humidity, and evapotranspiration were used as climatic parameters and all the data covered the time episode from 1971 to 2005 in a monthly time step. Raw forecast data were obtained from the Coupled Model Inter comparison Project phase 5 (<http://climexp.knmi.nl/help.cgi?id>) multi-model dataset for the period of 1971 to 2044.^[45] The climatic variables, like temperature, precipitation, relative humidity, and wind speed projections, were involved in CMIP5 under three emission scenarios (RCP) for 2006-2044. Therefore, all the scenarios, including RCP 2.6, RCP 4.5 and RCP 8.5, were applied. In order to do the simulation of climate variables for the meteorological stations, the latitude and longitude of the stations were chosen. This could provide the simulation points which are the adjacent points to the particular observation points.

2.3 Taking out the climate data

The Royal Netherlands Meteorological Institute KNMI^[46] managed and updated the Climate Explorer^[45] since 1999. The Climate Explorer (CE) is a web-established product for climatic research, which contains widespread collections of climatic data sets and examination tools. By doing free registration, researchers have ability to discover and download an assortment of cli-

matic data sets, upload their own time series, and make improved data.

The CE was applied for this paper: A) to discover and download accessible future climate data and developed time series; B) to define climate signal in great resolution time series; and C) to utilize climatic data to compute different drought indices and control future drought happenings.

2.4 Investigation of data sets

CE provides climate data sets in the outline of time series (station data and climate indices) and gridded fields (observations and reanalysis fields). All data sets may be retrieved by selecting the suitable time series or fields format on the CE web page. For climatic analysis, monthly time series and fields are most appropriate. Through choosing a time series of monthly station data (*i.e.* precipitation and temperature), CE provides the occasion to make a choice established on a station name. Furthermore, a minimum amount of years of data accessibility may be announced, as well as a series of years for which data may be available, and an elevation range. The study searched for the stations nearest to the Esfahan ($50^{\circ} 24'$ to $55^{\circ} 24'$ longitude and $30^{\circ} 11'$ to $34^{\circ} 11'$ latitude and elevation of 2300 m a.s.l) and applied minimum 30 years of monthly data accessibility. CE provides the selection to improve data for a particular grid point for the region. The raw data could be accessible in column format. Thus, adjusted time series data of precipitation and temperature for the stations (with given grid point) in Borkhar which were accessible were taken out.

2.5 Climate change models

Normally, climate change predictions prepared through models are not affiliated with the 'real' natural environment as a result of suspicions and data errors in the models. The newly CMIP5 consequences focus on fill this gap with a better resolution for the models and also with new climate change scenarios. In this paper, several productions from climate models using monthly output from 38 GCM (with 38 ensemble) which contributed in the CMIP5 were used. The novel models are more diverse and more improved compared to the CMIP3. Furthermore, the CMIP5, new models for forecasting climate change applying several scenarios, like "Representative Concentration Pathways" (RCP) were improved through Van Vuuren *et al.*^[21] This model could be applied in order to forecast the GHG alleviation potential. Model scenarios which were used in this research contained historical simulations and future forecasts. The historical models were through observed natural and anthropogenic

atmospheric composition changes spanning 1971-2005; they were utilized to provide a baseline against which to determine climate change in future projections. The future forecast was attained through forcing from the RCPs. Contrasting the Special Report on Emission Scenarios (SRES) that proclaimed the climate forecasts for the previous CMIP experiment (CMIP3), the CO₂ attentiveness in RCP2.6 is lower than B1, in RCP6.0 is a little higher than in A1B, and in RCP8.5 it exceeds A2. In this paper, all the RCP scenarios were used for 2006-2044. However, the severest potential GHG path (RCP 8.5) for the 21st century could make the strongest planning adaptation to mitigate the potential climate change impacts on water resources. Numerous ensemble members are accessible for each CMIP5 scenario for the given model. Supposing that there are sufficient models in the ensemble to manage a reliable evaluation of a potential climate change signal, only one ensemble from each CMIP5 model (total 38 models) and scenarios of RCPs were used in this paper. The historical data was from 1971 to 2005 and the data modelled for near future (2006-2044). The variables used were: precipitation, temperature, relative humidity and wind speed. The purpose of making 38 coupled GCMs for the different scenario of RCPs is to represent the hesitation in climate effects rising from future climate modelling. Furthermore, biases in climate variables like precipitation must be attended to; if not they will expand into the calculations for the following years. In order to resolve the resolution troubles and possible errors in GCM results, the GCM was downscaled statistically to the meteorological stations individually. Nevertheless, in order to reduce the model error and increase the resolution accuracy this study applied an easy downscaling method to increase the accuracy of the model. Several downscaling methods try to develop daily timescales. In this paper, as a result of data accessible, only monthly average climate data are needed and thus determining the high-frequency changeability (the intent of more compound methods) is not essential. In order to eliminate bias between the GCM and reality, monthly precipitation and temperature time series from GCM and observations for a particular site for the similar reference episode is desired, which is represented through $X_{p,gcm}$ and $X_{p,obs}$ correspondingly. Additionally, the production from the GCM for some future episode of the equal length as the reference episode, $X_{f,gcm}$ was needed. The question arises in what way to best mix these three sources of information into the most accurate projections of the unidentified future observations $X_{f,obs}$ to use as input for the water balance model. This current paper developed a general method considering explicitly the change factor. The change factor is alike to delta change approaches applied for weather gen-

erators. Nevertheless, the technique applied here is easier; an equally moved and scaled version of the observed time series was used for the future instead of a series taken from a weather generator. The change factor methodology applied the observed monthly variability and changes in monthly mean and variance as simulated via the GCM. In the simplest case this is the “delta method”, where the monthly change is supposed to have the equal magnitude in the future and reference periods, and the corrected monthly data is shown in Equation (1):

$$X_{DEL}(t) = X_{p,obs}(t) + (X_{f,gcm} - X_{p,gcm}) \quad (1)$$

where the time mean is represented via the bar above a symbol and the result of the bracket ($X_{f,gcm} - X_{p,gcm}$) is identified as a climate signal.

However, in a more general case, deliberating changes in variance is shown in Equation (2):

$$X_{(f,obsm,y)} = [\bar{X}_{f,gcm_m}] + [\bar{X}_{p,obs_m} - \bar{X}_{p,gcm_m}] \times \left[\frac{\bar{\sigma}_{f,gcm_m}}{\bar{\sigma}_{p,gcm_m}} \right] \quad (2)$$

where $X_{(f,obsm,y)}$ indicates the unknown future observation value of variable X for a particular month, m, and year, y. The variables comprise temperature, rainfall, relative humidity, and wind speed; X_{f,gcm_m} represents the mean future simulation for a specific month and episode of years (such as 2006 to 2044). X_{p,obs_m} is the mean present-day observed climate for a specific month averaged throughout all years of the historical episode (1971-2005), as measured from the meteorological stations in the study area; X_{p,gcm_m} indicates the mean simulation from GCM for a particular location for the reference period (e.g. 1971-2005); $\bar{\sigma}_{f,gcm_m}$ and $\bar{\sigma}_{p,gcm_m}$ denote the standard deviations of the raw model output for the future and present-day episode for a particular month. In order to select a model (among 38 models) and apply its climate data as an input to the hydrology and water balance model, CDF technique was applied. With the CDF technique, a model with the minimum bias in the raw precipitation could be chosen. The key reason for this selection is established on the hypothesis that GCMs with an accurate current climate will have an accurate climate change signal.

2.6 Drought indices

There are several studies about drought indices, like Normalized Difference Vegetation Index (NDVI), Reconnaissance Drought Index (RDI), Comprehensive Meteorological Drought Index (CMDI), Standardized Precipitation Index (SPI), and so on.^[23-27] The choice of indices is mainly related to research purposes (e.g., drought defence and reservoir process, water supply organization,

ecosystem organization and wetlands). In this research, three drought indices, SPI, SRI, and GRI, were used for drought defense and help water managers make proper planning during drought conditions.

2.6.1 Standardized Precipitation Index (SPI)

SPI can be known as the most common meteorological drought index^[28] and is based on rainfall data at a particular site. The sums of rainfall across a particular time period, the supposed cumulative scale, are applied to improve the cumulative probability distribution of the time series.^[29] Commonly a gamma distribution can match (applying the maximum likelihood method) the sum of the observed rainfall, while further distributions can be applicable as well.^[30] In order to contrast the SPI values over several times, the quantiles of gamma distribution are converted into standard normal variables. Thus, the negative principles of SPI show smaller than median precipitation and positive principles represent bigger than median situations.^[31] In this study, the SPI-12 was calculated by applying 12-month accumulated sums of rainfall. The selection of that accumulation scale was determined, considering the relationship with the inter-annual changes in rainfall and the significance of further indices was investigated.

2.6.2 Standardized Runoff Index (SRI)

The Standardized Runoff Index (SRI), reported by Shukla,^[23] is described in the same method as SPI with runoff variable applied as a substitute of rainfall. Stream flow, as an element of the hydrological cycle, is associated with penetration, dynamics of ground water, shallow runoff, soil moisture, and so on; thus the time-reaction of runoff in contrast to rainfall is related to the features of the basin: magnitude, complexity, land use, etc.^[32] Therefore, SRI can consider other features of the hydrologic series that are applicable in various catchments and are complicated for simulation. Consequently, the estimation of SRI as a supplement to SPI is appropriate. For upcoming climate predictions, stream flow is modeled by applying a rainfall-runoff model. In this research, the WEAP model was applied and its calibration was done (manually) using observations from the historical period (1971-2005) and its validation was based on observations from the years 2006-2008. WEAP is a water balance model and is distributed model. In this model one gauge station is used. Based on data availability, this research used WEAP model to calculate surface runoff. A wide explanation of the model is presented.^[32] Daily rainfall, air temperature, and potential evapotranspiration were applied as input variables to the WEAP model. The main advantage of WEAP is the integrated approach for simulating and optimizing water resources systems and orienting them in

line with policies.^[32] It considers needs (water patterns, equipment returns, reuse, costs and allocations) in line with resources (surface flows, groundwater, reservoirs and water transitions) and using linear optimization for the best solution.^[32]

WEAP can be used in urban and agricultural systems, independent basins or complex river systems.^[32] It can cover a wide range of issues such as needs analysis, water protection, rights and allocation privileges, simulation of surface and underground waters, reservoir operation, hydroelectric power generation, pollution control, environmental requirements, vulnerability assessment and cost benefit analysis.^[33,34] More details about the WEAP model is shown in Javadinejad *et al.*^[35]

The input data of the model included census statistics, which was extracted from the report of a consulting company (cited from the website of the Statistics Center of Iran).^[2] The per capita consumption of water was estimated at 73 cubic meters per person over a year.^[37]

The level of cropping and water requirement in each region were extracted from the report. The average of 34 years of discharge of each river basin as well as the amount of harvesting from wells were also obtained and entered into the model.^[38]

The evaporation rate was calculated from the level of the dam and the surface of the basin was calculated using the Penman Monteith method. Climate change forecasting data and future weather forecasting were obtained from the Climate Explorer online data and statistical down scaling method used.^[39] For this work, the climate data sets were obtained from the Koninklijk Netherlands Meteorologisch Instituut (KNMI) which cooperated with observer station data to project the historical and future climate models for Iran and the study area. The observational surface temperature (°C) and monthly precipitation (mm/day) data cover the time period from 1971 to 2005 in a monthly time step. Raw projection data are retrieved from the Coupled Model Inter comparison Project phase 5 (<http://climexp.knmi.nl/help.cgi?id>) multi-model dataset for the period of 1971 to 2100. CMIP5 includes the climatic variables such as temperature, precipitation, relative humidity and wind speed projections under four emission scenarios (RCP) for 2006-2100. However, the severest scenario (RCP 8.5) is used. To obtain the simulation of climate variables for the meteorological stations, the latitude and longitude of the stations were selected. This gave the simulation points which are the nearest points to the given observation points. Then future meteorological data was included in the CROPWAT model and the net irrigation requirement was calculated. The projected future water per capita consumption in urban and industrial areas was assumed with a population growth

rate of 2.5% and then all re-information was included in WEAP to simulate runoff for future years.

Analysis of the goodness of calibration of the WEAP model between observed and simulated runoff was assessed via the Nash-Sutcliffe (NS) efficiency. The 3 factors of the model were calibrated for the episode of 1971-2005 and validated for 2006-2008. The achieved NS efficiency was about 0.86 for the validation phase.

2.6.3 Groundwater Resources Index (GRI)

GRI is similar to SPI and SRI and it can reach by normalization method. The groundwater level data is reached by GMS model. GRI can be measured using Equation (3):^[53]

$$GRL_{y,m} = D_{y,m} - M_{D,m}/SD_{Dm} \quad (3)$$

where $GRI_{y,m}$ shows the index principle in month m of the year y ; and $D_{y,m}$ indicates the principle of water table in the specific month m of the year y ; and $M_{D,m}/SD_{Dm}$ represents mean and standard deviation of water table in month m of the year D .

2.7 Drought group corresponding to SPI, SRI, and GRI

The drought indices (SPI, SRI and GRI) can provide sign of the relative dryness/wetness. Because of the standardization to normal distribution, the three indices have equal ranges and are equivalent, which permits a measurement of drought categorizes. Therefore, the most common group scheme is displayed in Table 1.^[54]

Table 1. SPI, SRI, and GRI classification^[2,57]

Drought groups	Principles
Extremely wet	> 2
Very wet	2-1.5
Middling wet	1.5-1
Normal	0.99 to -1
Modestly drought	-1 to -1.5
Harshly drought	-1.5 to -2
Extremely drought	< -2

2.8 Examination of Mann-Kendall (MK)

The MK trend test statistic, S , in Equation (4)^[54] can be applied to examine the trend of water table:

$$S = \sum_{i=2}^n \sum_{j=1}^{i-1} \text{sign}(x_i - x_j) \quad (4)$$

In the equation shows the number of observations, x_j indicates the j th observation, and sign represents the sign function that is calculated from Equation (5):

$$\text{Sign}(x_i - x_j) = \begin{cases} \text{if}(x_i - x_j) < 0 & -1 \\ \text{if}(x_i - x_j) = 0 & 0 \\ \text{if}(x_i - x_j) > 0 & +1 \end{cases} \quad (5)$$

By considering the hypothesis that the data are objective and definitely dispersed, the mean and variance of the S statistic are calculated in Equation (6):

$$\text{Var}(s) = \frac{n(n-1)(2n+5) - \sum_{i=1}^n (ti-1)(2ti+5)}{18} \quad (6)$$

In the equation shows the amount of groups of tied ranks, each with t_i tied observations. The original MK statistic, indicated via Z , may calculated by Equation (7):

$$Z = \begin{cases} \frac{s-1}{\sqrt{\text{Var}(s)}} \text{if } s > 0 \\ 0 & \text{if } s = 0 \\ \frac{s+1}{\sqrt{\text{Var}(s)}} \text{if } s < 0 \end{cases} \quad (7)$$

If $-Z_{1-\alpha/2} < Z < Z_{1-\alpha/2}$ hence the null hypothesis of no trend may hold at the significance level of α . If not, the null hypothesis can be rejected and another possibility hypothesis may agree at the significance level of α . The result of Mann Kendall test is shown in section 3.

2.9 Cross-correlation function

In order to determine the concurrence or absence of concurrence of hydro-meteorological drought by applying GRI, cross correlation function has been applied. The likelihood of estimating the correlation coefficient in the preferred time step containing positive and negative phases is the most significant benefit of cross-correlation technique. SPSS Software was applied to perform the calculations. If X_i and Y_i with $i=1, 2, \dots, N$ are two variables, the R-principle of cross-correlation among them is shown in Equation (8):

$$R_{ccf} = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - d - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^n (y_i - d - \bar{y})^2}} \quad (8)$$

For $\left\{ \begin{array}{l} \text{lagtime } 0, \pm 1, \pm 2, \pm 3, \dots \\ f : i - d < 0, i - d > N \end{array} \right\}$

In the formula, the X and Y values show the average principle of each i X and i Y time series, correspondingly. Usually, $i \leq 0$ and $i \geq N$ are not deliberated and the principle of the cross-correlation coefficient is usually estimated as $-1 < R < 1$.

Statistics of piezometric wells for the episode of 1971-2005 were applied to discern the trend of level of groundwater changes and to estimate the discharge and recharge and serious elements in the region. Furthermore, statistics of rain gauge and hydrometric stations in the basin were applied to monitor the drought and its effect on extraction and/or recharge of groundwater supplies. Standardized Precipitation Index (SPI), Standardized Runoff Index

(SRI), and Groundwater Resource Index (GRI) were applied to display the drought, discern the trend of discharge and changes in groundwater level.

2.10 Arrangement of Iso-piezometric map applying technique of interpolation

Iso-piezometric map is the co-depth lines of the level of groundwater displayed as contour lines. The reduction in the height of lines from out into the in indicates recharge within the area, whereas the rise in the height displays flow in the basin. A number of nearby accessible wells have been operated to observe the depth of water to make the maps. Map of groundwater level was defined with the extraction of water from the wells and obtaining the groundwater level and interpolation of co-height levels. Inverse Distance Weighted interpolation technique (IDW) via Arc/MAP software was applied to construct the Iso-piezometric map. Each of the interpolation approaches is established on the concept that the relationship and likeness of neighboring items estimated more than of faraway items. It is supposed that the relationship and likeness of neighboring items is relative to the distance between them and that it can be expressed like an inverse of the distance of each item from the neighboring items and is shown in Equation (9):

$$ZO = \frac{\sum_{i=1}^N Zi di^{-n}}{\sum_{i=1}^N di^{-n}} \quad (9)$$

where ZO indicates the principle of variable Z at point i; and Zi represents the value of sample at point i; di^{-n} shows the point to point distance of assessed samples; and n indicates the exponent defining the weight established on the distance.

3 Results and discussion

3.1 Discovering the position of hydro climatic variables

There are changes in annual rainfall in the basin. Figure 3 indicates the average yearly precipitation changes in the Isfahan-Borkhar basin during 2006-2044. The figure indicates that there was a trend for decreasing rainfall in the study area from 2006 to 2044 for all RCP scenarios. The maximum and minimum rainfall, correspondingly, was measured in winter (in March with a mean of 27 mm) and in summer (in September with a mean of 0.1 mm). Alternatively, rainfall changes displayed a decreasing trend of rainfall, which is in concurrence with the results of Mafi-Gholami *et al.*^[40] and Javadinejad *et al.*^[41] in the coastal area and the arid area of Iran correspondingly. Figure 4

represents changes of input runoff in the basin and results showed that a strong relationship between discharge and rainfall changes in the study area. The change of flow was considerable and there was a decreasing trend for the future time period (2006-2044) for all RCP scenarios. The average amount of discharge for 4 decades was anticipated to be 123.32 m³/s under the severest scenario of RCP 8.5, and the average amount of discharge for the RCP 2.6 and RCP 4.5 was forecasted as 176.8 m³/s and 173 m³/s, respectively. Also, the minimum and maximum discharges, according to the lowest and greatest precipitation values, respectively, were forecasted in summer and in winter. Results indicated a decreasing runoff trend which was in concurrence with the outcomes of Khosravi *et al.*,^[42] Rahimi *et al.*^[43] in some areas of Iran, however, in comparison with the results of Han *et al.*^[17] in China, and Kitoh^[48] in Turkey they showed an increasing trend of runoff. It appears human actions can effect the decrease of runoff more than hydro-climatic elements.

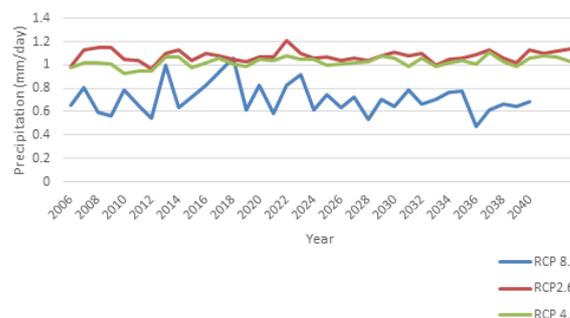


Figure 3. Average yearly precipitation changes in the Isfahan-Borkhar basin (2006-2044)

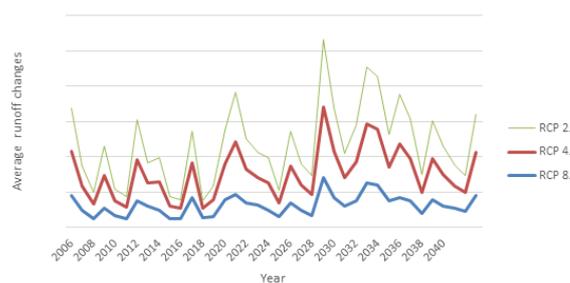


Figure 4. Average yearly runoff changes in the Isfahan-Borkhar basin (2006-2044)

The variations of groundwater level in the basin showed a decreasing trend during 2006-2044 for all RCP scenarios Figure 5, which accurately coordinated with low rainfall and the drought years in the region. This outcome was in concurrence with the outcomes from other parts of Iran.^[42-44] The main reason for this drought was identified to be the population increase and unsuitable spatial population dispersal, disorganized agricultural seg-

ment, misconduct and desire for improvement.^[16] Figure 5 shows that the average groundwater table for the severest scenario (e.g. RCP 8.5) was 1534 and for the scenario of RCP 2.6 and 4.5 it was anticipated be 1536.32 and 1535.15, respectively. In addition, groundwater fluctuation during 2006-2044, as shown in Table 2, showed a significant decreasing trend.

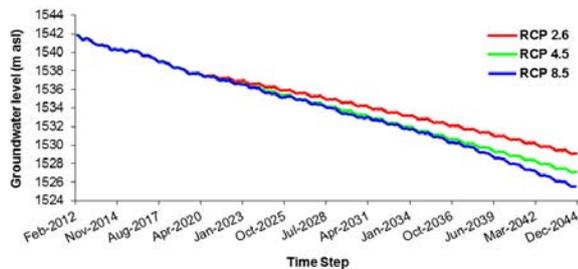


Figure 5. Average yearly groundwater table changes in the Isfahan-Borkhar basin (2006-2044)

Table 2. Groundwater table fluctuations in the study area

Groundwater level fluctuation	Z value	Significance in the confidence level of 95%
7.29	-2.35	Yes

3.2 Discovering the association of climatic with hydro-meteorological drought

Because of the couple of characteristics, the SPI is a useful index of meteorological drought principally and so in this study SPI was applied. It may be estimated for different timescales (enlargement episodes), and calculated SPI quantities can be compared at different time and space scales.^[45-47,49] Nevertheless, the SPI also has two significant disadvantages, which were recognized by Gidey *et al.*^[15] The quantities of SPI for various lengths of observation records can be different, because of dissimilarities in the shape and scale factors of the fitted gamma (or further) distribution for various lengths of records. Furthermore, the quantities of SPI are sensitive to the shape of the possibility distribution that is matched to the observed data as a measurement of normalization procedure. The GRI is a normalized drought index that can be used to estimate drought in groundwater level. The GRI uses a similar method like SPI and SRI. Limitations in the SPI can influence GRI, except that a suitable normalized distribution was selected. The problem of distribution matching can decrease when GRI is developed through approving a nonparametric method for the normalization of the time series of groundwater level. It can be obtained by the transformation of normal scores. Applying the normal scores transforms consequences in a distribution of principles of GRI which are normal. The method is strong when applied to historic time series, though further testing

and verification for any over matching would be necessary in order to apply to forecast principles of GRI. For the reason that the non-parametric normal scores transform is applied to normalize the time series of groundwater level for estimating GRI, the duration of record is not a problem in the same way as it is for the SPI evaluation. For example, a gamma or further distribution is not matched and the trouble of inconsistencies among matched parameters for records of various durations does not happen. Because GRI is a drought index which is normalized like any other normalized drought index, the principles of GRI will reveal the episode and duration of the time series that is being normalized, in this situation groundwater levels must be established on similar duration records. For the reason that groundwater level is an incessant variable, GRI could not measure for a series of timescales in an approach similar to SPI. However, if separate recharge data (observed or simulated) are available, then the GRI methodology can be applied for a series of timescales applying amassed recharge. On the other hand, differencing consecutive monthly levels of groundwater observations would make a change in time series of groundwater level that would also allow the GRI approach to be used across a series of timescales. Koutroulis *et al.*^[51] applied monthly groundwater imprisonment, an output from a distributed water balance model, as the basis for an SPI-like index of groundwater drought. Mendicino *et al.*^[53] applied monthly groundwater imprisonment, a production from a dispersed water balance model, as the source for an SPI-similar index of groundwater drought. Across a series of timescales, it can accumulate however, in their work they focused on only one month accumulation episode. Nevertheless, the most important problem associated with the function of SPI time series is that SPI is a drought index that has principles that are similar in geographical feature (*i.e.* principles that are unchanged through geographical alterations). On the other hand, other drought indices, such as soil moisture, stream flow and groundwater drought (*e.g.* GRI), can be affected by location significantly. The GRI time series reveals not just the meteorological drought and GRI not just known as a driver to show the extension of meteorological drought, but GRI can also be affected through local and procedures of site particular recharge and also through regional to site-particular saturated flow procedures. Therefore, the recharge and procedure of saturated flow have a relationship with the time series of GRI and also the GRI can be affected by physical geography characteristics. In addition, hydro-geological circumstances of observation boreholes can affect the GRI. Result of this study showed that SPI, SRI and GRI had linear correlation. Also the three drought indices are

Table 3. Mean cross correlation coefficients for SPI, SRI and GRI in Borkhar area

Delay steps	0	1	2	3	4	5	6
SPI-GRI	0.39**	0.41**	0.42**	0.44**	0.46**	0.50**	0.52**
SRI-GRI	0.54**	0.54**	0.55**	0.55**	0.55**	0.54**	0.50**

Notes: **Significant level ($P < 0.05$)

useful parameter to show drought features like drought duration, and also the indices are able to show basin characteristics significantly. The GRI applies a normalization method to make incessant drought index for time series. One of the advantages of GRI is using the mean monthly groundwater level. However, other drought indices just use a mean hydrological baseline in the calculation. The normalized drought indices, like GRI, and the method to measure the indices are established on a specific threshold which can measure the absolute values of drought. For example, for estimating GRI, the values of groundwater levels which are below or above the threshold can show the dry and wet periods. In previous works such as Wu *et al.* [50,52,55] the threshold for estimating groundwater drought was applied and also return periods of groundwater drought were calculated. In another research, the threshold for of groundwater level was used to estimate the periods of low flow for historical time periods.

Table 4. Result of Mann-Kendall test

Region	Index	H(0)	P value	Trend
Borkhar basin	SPI	True	0.022 *	Yes
	SRI	True	0.025*	Yes
	GRI	True	0.030*	Yes

Notes: **Significant level ($P < 0.05$)

The results showed that with Mann-Kendall test the trend for increasing meteorological and hydrological drought is increase. Table 4 showed the Mann-Kendall test. However, in all previous researches the estimation of all drought indices for future time and for seasonal period did not perform well. Low and high groundwater levels in some regions highly depended on seasonal changes principally in flashy, seasonal aquifers. The method of threshold in the drought indices can measure features of drought like intensity, episode, and return period of drought. Also the threshold has been improved to show changes in seasonal time series of hydrologic parameters. Fendekova and Fendek [11] applied a threshold technique in order to illustrate drought in the base flow of groundwater in a catchment, however, the issue of seasonality was ignored because only average yearly base flow was analyzed. The significant difference between the normalization and threshold techniques is that the threshold method cannot make a prolonged index of drought based on temporal features of drought records. So, it cannot be used for spectral or wavelet analysis which are established on con-

tinuous time series of data. Therefore, GRI can provide continuous time series of groundwater and can analyze groundwater level based on both threshold and normalization method. The GRI index can explain groundwater drought properly. In some previous researches, such as Nayak *et al.*, [56] the drought indices were only based on a normalization method. In their study they provided the precipitation data and groundwater level data for a catchment which had 541 wells. The study was based on GIS processes and they discovered the spatial-temporal dynamics of drought but they did not analyze and calculate the correlation between different drought indices. In another study, the SPI was used as a normalized method and an index for vegetation health was used to understand the effect of drought on vegetation, however, an index for estimating soil moisture drought or groundwater level drought was not considered. In the study of Le *et al.*, [57] the relationship between GRI and lithological features of a basin was analyzed. Their result showed that there was a significant correlation between GRI and lithological features. Also, in a research, which was done by Reynolds *et al.*, [58] the karstic spring discharge for three springs for monthly scale in one year was analyzed and the association between meteorological droughts and time series of karstic spring discharge was investigated. Their results indicated that the discharge of karst system only depended on the 12 months of SPI which was established on the accumulation data and it was extended to meteorological drought. Therefore, the deficit in the spring discharge resulted from the extended meteorological drought. This paper used a normalization method and developed the method by analyzing the relationship among meteorological, hydrological, and groundwater droughts. Also this study used cross correlation between SPI, SRI and GRI in order to find the extension of drought from climate parameters to hydrological parameters. Cross correlation analysis can show where meteorological drought can cause groundwater drought severely and how meteorological drought can effect the deficit of groundwater level. Unlike previous researches which used drought indices for short time period such as 3, 6 or 9 months, this current paper applied long time periods for different meteorological and hydrological drought indices. Similar to the previous studies, this paper showed a lag time between meteorological drought and groundwater drought. Also, this study presented a more widespread cross correlation among

meteorological, hydrological, and groundwater droughts. The key advantage of examining groundwater drought index is that groundwater level can be estimated during dry and wet years and also in comparison with meteorological and surface hydrological drought, the groundwater drought index can represent the hydro-geological features of a catchment strongly. Some previous studies mentioned that water balance evaluation can be measured by using the Standardized Precipitation-Evapotranspiration Index (SPEI) and by considering the relationship between SPEI and SPI. The SPEI is used in the UK in order to measure groundwater shortage and calculate the effects of temperature and evapotranspiration on groundwater recharge especially for the seasons of autumn and winter. But still, it is not clear what the long term effects of temperature and evapotranspiration on the recharge of groundwater in UK are. Therefore, the study of Hui *et al.*^[18] suggested that if different drought indices, such as meteorological, hydrological, and groundwater drought indices were used, then the influence of temperature and evapotranspiration on groundwater level and groundwater recharge can be analyzed. Although SPEI can show water balance and the index applies both precipitation and temperature in order to estimate drought characteristics, however, this study used precipitation, temperature, evapotranspiration, humidity and so on to model water balance and calculated the surface hydrological drought (*e.g.* SRI) and then calculated GRI. The SPI and SRI indices were analyzed at 12 month time scales; GRI was measured monthly and the cross correlation coefficient was calculated concurrently to 6 month delay. The cross correlation coefficient concurrently at 6 month lead times is indicated in Table 3. Significant concurrent correlation between SPI and GRI and between SRI and GRI at 12 month time scale was found, while the biggest correlation happened with a 6 month interval. Changes in the of groundwater level in relation to SPI and SRI revealed that hydro-meteorological drought happened concurrently in the Borkhar basin. So, Figure 6, Figure 7 and Figure 8 show meteorological, surface hydrological, and groundwater droughts, respectively. These figures showed that the number of dry years are more than the number of wet years and also the intensity of the dry years are more than the intensity of wet years. Based on these figures, there was wetness in some years, while there was a drought trend in the time period (2006-2040). While Potopová *et al.*^[59] investigated a lag time among meteorologic and hydrologic droughts and flow, indicated concurrent happening of groundwater drought and hydrological drought. The climatic and hydrologic droughts in arid and semi-arid districts happened with seasonal rivers concurrently. Previous studies did not combined three different drought

indices and did not analyzed drought characteristics under the new climate change models and new climate change scenarios. However, this study fills the gaps.

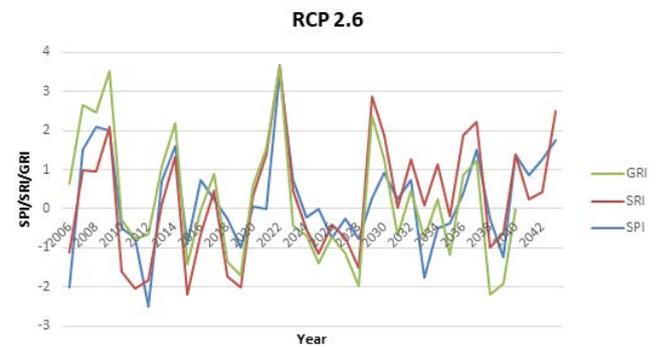


Figure 6. Drought indices changes in the Isfahan-Borkhar basin under the scenario of RCP 2.6 (2006-2040)

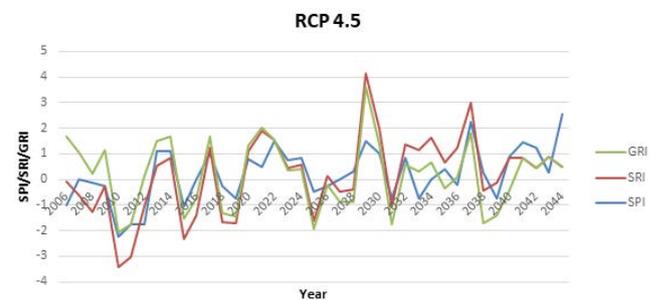


Figure 7. Drought indices changes in the Isfahan-Borkhar basin under the scenario of RCP 4.5 (2006-2040)

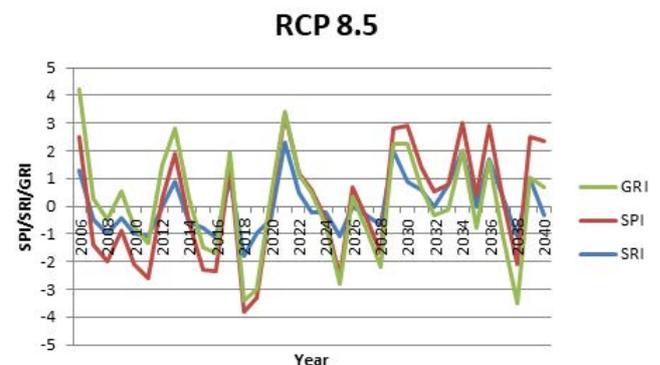


Figure 8. Drought indices changes in the Isfahan-Borkhar basin under the scenario of RCP 8.5 (2006-2040)

4 Conclusion

In this study the new climate change model of CMIP5 under different scenarios of RCP 8.5, 4.5 and 2.6 was used for modelling climate parameters and then used as input data for a hydrological model. Hence, three different drought indices were calculated. The SPI, SRI, and GRI indices indicated various episodes of wetness and climatic, hydrologic, and hydro-geologic droughts. Climatic and hydrologic droughts showed a significant positive relationship, which denotes that meteorological,

hydrological, and groundwater droughts happened concurrently. The three kinds of drought showed a significant positive association with the variations of groundwater level. Also, hydro-geologic wetness and drought episodes happened with the occurrence of climatic and hydrologic wetness and drought episodes; the maximum association was found at the time scale of 6 months. Considering the flow points, the Borkhar basin was in the vulnerability of subduction and degradation, with a loss of 1534, and 1535, and 1536.32 groundwater table for the scenario of RCP 8.5, 4.5, and 2.6, respectively, in the four decades. A considerable change in the water level in autumn and winter was found, because more than 91% of rainfall happened in autumn and winter. The hydro-meteorological drought in the Borkhar basin is changing in the long term. The aquifer system of the basin, like a significant water supply for agricultural, industrial, and municipal consumption, is in great stress. Decrease in water withdrawal is essential and improving artificial recharge in the region may be useful. The main findings of this study showed that combination of different drought indices can show drought characteristics very well and with using new climate change model and new downscaling model and new climate scenario, drought conditions can present properly. Therefore, application of the model especially in regional scale can show the effects of climate change on drought features more precisely. Also, the effect of climate change on meteorology factors can effect on hydrological factors but with different intensity.

Conflict of interest

I or any of my co-authors are not employed by the Government of Iran. There is no conflict of interest.

Data availability

Some or all data, models, or code generated or used during the study are available from the corresponding author by request.

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