The effects of hydrological drought on water quality

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Abstract Management and conservation of water resources are critical to human welfare. The high demands for water of an increasing world population have focused our attention on water resources quality and quantity management. Climate change is likely to have significant effects on hydrological regimes (i.e. low flows and high flows), affecting both water quantity and water quality. Although climate change impacts on water quantity are widely recognized, little is known about the impacts during low flow periods (i.e. hydrological drought). The objective of this study was to assess the effects of hydrological droughts on the water quality in Mazandaran Province, Iran, based on analysis of the low flow index and existing water quality data. In view of this, 1-day low flows, as a measure of hydrological drought, were calculated for 15 water years (1991–2006) at six monitoring stations. Eleven water quality parameters were extracted during the low flows from the water quality data. Water quality during these droughts was investigated and compared to water quality during high flows. The pattern and magnitude of the statistically significant responses (t-test, $p < 0.05$) varied among sites, i.e. Cl^- and HCO_3^- at Sefidchah, Ca^{2+} at Gelvard, sodium adsorption ratio (SAR), Na^+ and SO_4^{2-} at the Abloo station, Mg^{2+}, Ca^{2+}, HCO_3^- and total dissolved solids (TDS) at Darabkola, and SAR, Cl^-, Na^+, electrical conductivity (EC) and TDS at Rig Cheshmeh. We can conclude that data regarding other environmental changes, such as land use, will be needed to further elucidate the response of water quality to droughts.

Key words hydrological drought; low flow index; water quality; Mazandaran province, Iran

INTRODUCTION

Drought is a complex natural hazard that affects some areas of the world every year. Hydrological droughts characterized by the reduction in lake storage, lowering of groundwater levels and decrease of streamflow may occur over one year or over several consecutive years, and often affect large areas (Smakhtin, 2001). The consequence is an increasing demand on a decreasing availability of water resources. Hydrological drought is crucial for various hydrological studies such as water quality management, determination of minimum downstream flow requirement for hydropower and ecological needs, irrigation system design and wastewater treatment. Droughts may be assessed using low flow indices, i.e. lowest annual flow for a given duration (e.g. 1, 7, 15 and 30 days), particularly droughts that occur in the same season each year (Tallaksen *et al.*, 1997). Low flow resulting from drought can affect water quality and aquatic biology through various physical, chemical and biological processes (Caruso, 2002) and can also aggravate water pollution.

The issue of the effects of extreme weather conditions, a possible result of climate change, on streamflow quantity has been extensively investigated in recent years. Studies showed different effects of climatic variability on high and low flows (e.g. Arnell, 1999; Hanson & Weltzin, 2000). Recently, investigations on the effects of climate change on water quality have also been carried out, mostly focusing on droughts (Zwolsman & van Bokhoven, 2007; van Vliet & Zwolsman, 2008; Elsdon *et al*., 2009). Mimikou *et al*. (2000) showed that water quality simulations under future climatic conditions entail significant water quality impairments because of decreased streamflows. Wilbers *et al.* (2009) demonstrated that the drought period of 2003 in the Dommel River, a tributary of the Meuse River in the Netherlands, did not significantly affect water quality.

In Iran the availability of water resources is critical during certain periods. River flows are strongly seasonal characterized by low natural flow during summer. The high frequency of droughts in the area makes it necessary to improve management strategies for water quality and quantity during dry periods. Surface water is not only a major source of drinking water in Iran, but also supplies public water utilities and accounts for almost all of the water supply to rural households. Therefore, knowledge of low flow quality and quantity interactions in streams is important for maintenance of the quantity and quality of water for irrigation, recreation, and wildlife conservation. Thus, it is important to determine the climatic, and in particular drought impacts on surface water quality. The aim of this study is to evaluate the effects of extreme low and high flows during drought and wet periods on water quality in Mazandaran Province, Iran.

MATERIALS AND METHODS

Study area description

The present study investigates the effects of drought on water quality at six stations in three cities (Behshahr, Neka and Sari) of Mazandaran Province in northern Iran (Fig. 1, Table 1). The study area is located in karstic region in Sari-Neka in the eastern part of Mazandran province and consists of year-round emerging springs and forested hills. Mazandaran Province is an important region for agricultural production, which directly depends on river water resources. Low flow frequency analysis will provide essential information regarding the risks of industrial development and water quality management during times of low flow, i.e. summer season, such as water pollution by pesticides and other industrial waste constituents. Such pollutants can also be harmful

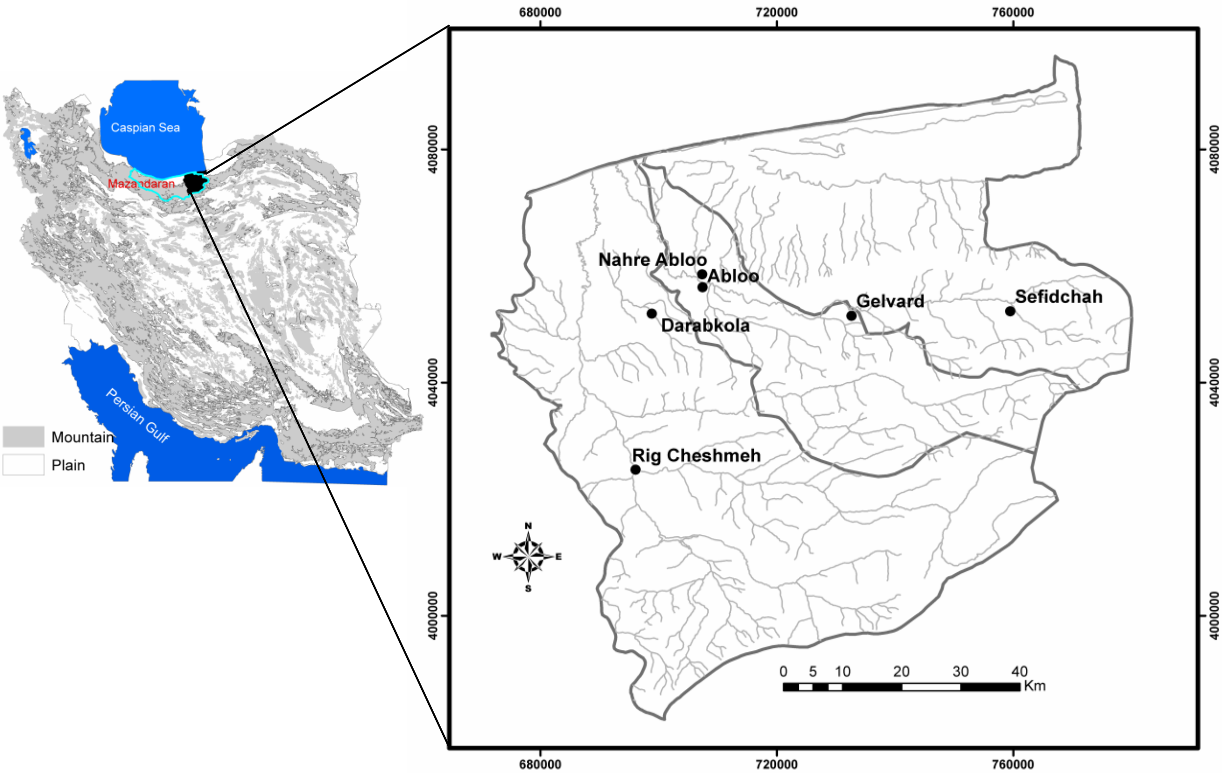

Fig. 1 Location map of the study area and monitoring stations.

Table 1 The details of selected monitoring stations in Mazandaran Province.

Station	River	Longitude	Latitude	Elevation (m)	Catchment area (km^2)
Sefidchah	Neka	53°54′	36°35′	1000	1043
Gelvard	Neka	53°36′	36°35′	600	1518
Abloo	Neka	53°19′	36°38′	70	1962
Darabkola	Neka	53°14′	36°33′	140	55
Rig Cheshmeh	Tajan	53°10′	36°21′	200	2715
Nahre Abloo	Neka	53°19′	36°39′	75	145

to fisheries downstream in the Caspian Sea and agricultural activities, which are the main source of rice production in the country. All rivers in the region originate in the Alborz Mountains, south of the study area. Summer rainfall is also important in the region. The mean annual rainfall in the region ranges from more than 1000 mm in the west to 300 mm in the east of the province. About 33% of all precipitation falls as snow in the mountainous area. The snowmelt period usually begins in mid-April and concludes in late April to early May.

Data collection

Hydrological data for 1991–2006 were evaluated. Two data sets were considered in the analysis:
(i) daily river discharges at six gauging stations that had no data gaps for the 1991–2006 period;
(ii) eleven water quality parameters for 1991–2006 including sodium adsorption ratio (SAR), electrical conductivity (EC), total dissolved solids (TDS), pH, bicarbonate (HCO_3^-), chlorine (Cl^-), sulfate (SO_4^{2-}), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), and potassium (K^+).

Data treatment and statistical analysis

The hydrologically-based low flow definition takes an extreme value approach in which the low flow is the smallest *x*-day average; a 1-day duration was selected in order to evaluate water quality parameter values during the same day. Therefore, lowest annual flow associated with drought conditions was evaluated for 15 water years (1991–2006). Moreover, the highest annual flow was selected to represent the wettest period for 15 water years (1991–2006). The normality and homogeneity of variance of the associated water quality parameters values during the drought and wet periods were tested by 2-tailed Kolmogorov-Smirnov and Levene tests, respectively. These statistical analyses were followed by a t-test for the identification of significant differences between drought and wet periods, and by a linear regression for the determination of significant relationship between the mean of water quality parameters and discharge at the monitoring stations during wet and drought periods. Statistical analyses were carried out using STATISTICA v6.0 (StatSoft Inc., 2001).

RESULTS AND DISCUSSION

According to the t-test, water flow differs significantly ($p < 0.05$) between the hydrological drought period and the wet period during 1991–2006 at the six selected monitoring stations (Table 2). Statistically significant differences ($p < 0.05$) were noted for physicochemical parameters, except for pH and K^+ concentration, (Table 2). However, the comparison showed that the pattern and magnitude of the response varied among stations, i.e. Cl^- and HCO_3^-, at Sefidchah, Ca^{2+} at Gelvard SAR, Na^+ and SO_4^{2-} at Abloo, Mg^{2+}, Ca^{2+}, HCO_3^- and TDS at Darabkola, and SAR, Cl^-, Na^+, EC and TDS at Rig Cheshmeh were significantly different between the drought and wet periods (Table 2). Differences for water quality parameters at Nahre Abloo were not detected when comparing the drought period to the wet period (Table 2). Although differences were not always statistically significant, the general pattern was that physicochemical concentrations were lower during the wet period than during the drought period at most of the monitoring stations.

The mean of the water quality parameter values at the monitoring stations, which had continuous discharge records during 1991–2006 particularly during both wet and drought periods, were evaluated using linear regression. The data analysis shows that during the drought period important and reliable correlations are found for SAR, Cl^-, SO_4^{2-}, and Na^+ and discharge (Fig. 2). However, there is a no statistically significant correlation between the water quality parameters and discharge during the wet period (Fig. 2). Dakova *et al.* (2000) found the best statistically significant correlation between hydrobiological indexes and discharge during the low flow period. Elsdon *et al.* (2009) detected minimal differences in water quality between land uses during a period of extensive drought. Zwolsman & van Bokhoven (2007) and van Vliet & Zwolsman (2008) demonstrated that water quality was negatively influenced by droughts, with respect to water temperature, eutrophication, major ions and heavy metals; they also indicated that the impact

Table 2 Mean and significant values of surface water quality variables in two drought and wet periods, 1991–2006 (shading indicates significant value).

Variables	Sefidchah Wet	Drought	p-value	Gelvard Wet	Drought	p-value
Discharge ($m^3 s^{-1}$)	2.6	0.1	0.00	9.3	0.8	0.00
SAR	0.9	0.7	0.13	0.5	0.5	0.81
K^+ (mg L^{-1})	2.2	2.1	0.79	1.8	1.4	0.13
Na^+ (mg L^{-1})	31.3	26.5	0.25	14.9	15.2	0.91
Mg^{2+} (mg L^{-1})	57.0	64.0	0.15	42.1	43.3	0.78
Ca^{2+} (mg L^{-1})	107.5	111.5	0.66	92.5	80.7	0.04
SO_4^{2-} (mg L^{-1})	139.6	118.3	0.34	62.3	53.6	0.47
Cl^- (mg L^{-1})	35.3	26.9	0.04	17.9	14.9	0.16
HCO_3^- (mg L^{-1})	236.3	272.3	0.02	213.7	208.0	0.70
pH	7.8	7.7	0.45	7.8	7.7	0.65
EC (µS cm^{-1})	640.2	646.1	0.88	464.9	437.9	0.33
TDS (mg L^{-1})	418.5	423.3	0.86	303.7	288.1	0.39
	Abloo Wet	Drought	p-value	Darabkola Wet	Drought	p-value
Discharge ($m^3 s^{-1}$)	21.1	0.5	0.00	4.9	0.2	0.01
SAR	0.4	0.7	0.04	0.4	0.8	0.08
K^+ (mg L^{-1})	1.7	1.6	0.66	1.5	1.9	0.10
Na^+ (mg L^{-1})	14.4	22.3	0.04	12.1	30.6	0.08
Mg^{2+} (mg L^{-1})	39.5	47.6	0.08	39.9	53.9	0.01
Ca^{2+} (mg L^{-1})	86.1	79.4	0.32	83.1	109.5	0.02
SO_4^{2-} (mg L^{-1})	44.6	74.6	0.02	44.5	72.5	0.15
Cl^- (mg L^{-1})	17.3	20.2	0.30	12.8	36.6	0.16
HCO_3^- (mg L^{-1})	206.6	212.9	0.68	205.4	271.5	0.01
pH	7.8	7.7	0.45	7.6	7.7	0.78
EC (µS cm^{-1})	436.5	483.7	0.20	801.0	639.1	0.70
TDS (mg L^{-1})	286.5	316.8	0.21	268.7	417.3	0.01
	Rig Cheshmeh Wet	Drought	p-value	Nahre Abloo Wet	Drought	p-value
Discharge ($m^3 s^{-1}$)	24.3	3.4	0.00	1.4	0.3	0.00
SAR	0.7	1.4	0.00	0.4	0.5	0.06
K^+ (mg L^{-1})	1.6	2.0	0.06	1.6	2.1	0.30
Na^+ (mg L^{-1})	25.5	53.8	0.00	12.8	17.7	0.06
Mg^{2+} (mg L^{-1})	48.3	62.4	0.06	41.6	42.8	0.74
Ca^{2+} (mg L^{-1})	123.0	129.7	0.64	82.6	90.1	0.20
SO_4^{2-} (mg L^{-1})	139.9	158.6	0.50	62.8	63.4	0.97
Cl^- (mg L^{-1})	27.6	60.6	0.00	14.6	17.5	0.21
HCO_3^- (mg L^{-1})	235.1	286.7	0.17	195.4	218.2	0.08
pH	7.8	7.9	0.31	7.8	7.7	0.42
EC (µS cm^{-1})	630.0	828.2	0.03	425.3	467.2	0.17
TDS (mg L^{-1})	410.1	537.9	0.03	277.9	307.0	0.15

of droughts on water quality will be greater when the water quality is already poor. Prathumratana *et al.* (2008) proposed TSS, alkalinity and conductivity as sensitive water quality parameters for monitoring impacts of changing climate in the lower Mekong River. In their study, negative significant correlations were generally found between discharge flow and dissolved oxygen (DO), pH and conductivity (from 0.2 to 0.9). Worrall & Burt (2008) observed decreasing dissolved organic carbon (DOC) fluxes and concentrations in the areas that had experienced severe droughts in British rivers. Osterholm & Astrom (2008) showed that the severity of individual summer droughts in the Pajuluoma acid sulphate area of Finland had little or no impact on the water quality during subsequent autumn and spring.

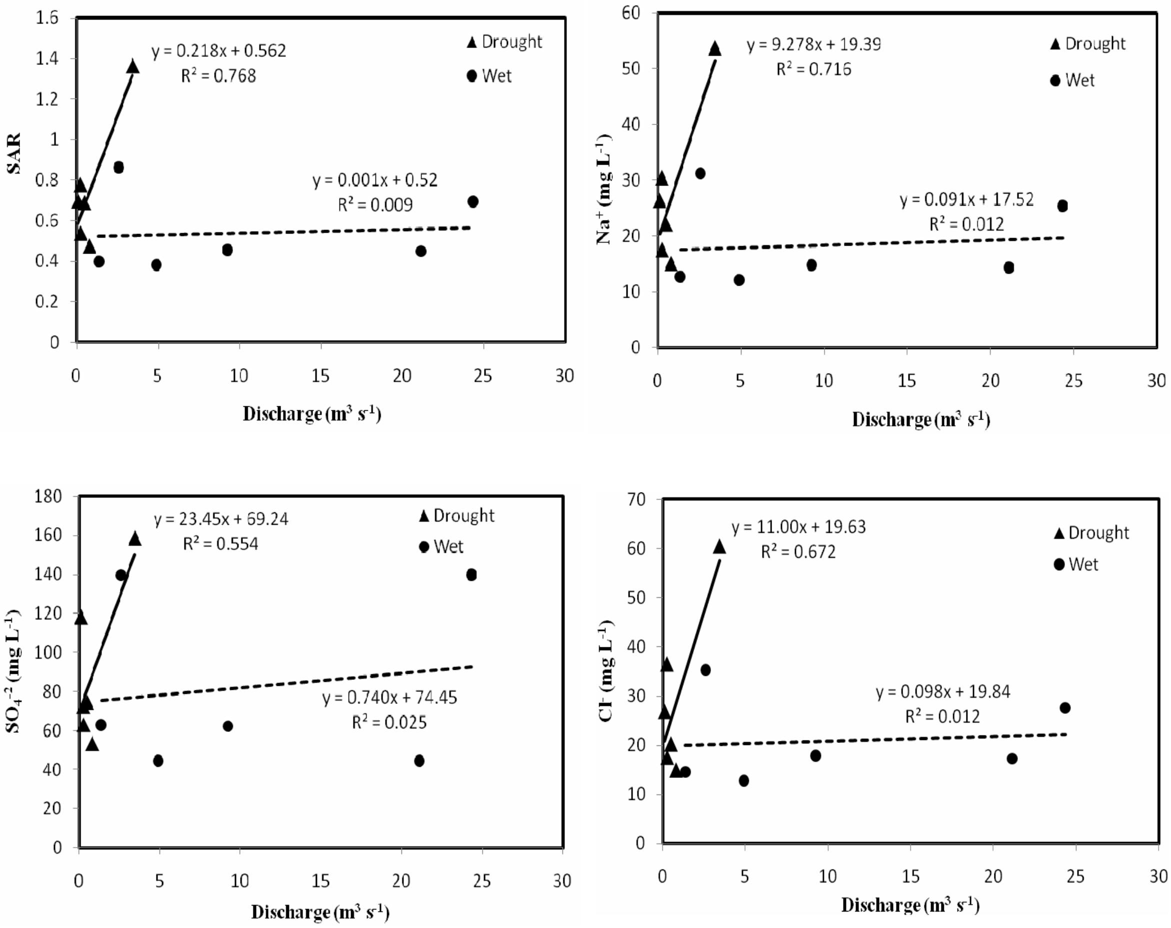

Fig. 2 Relationship between discharge and water quality parameters in drought and wet period.

Global climate change projections indicate changes in rainfall, causing increased frequency and severity of low flow in some regions (Sheffield & Wood, 2008). Low flow conditions are determined by a suite of natural and anthropogenic factors and are an integral part of every river regime (Smakhtin, 2001). The basis for estimating low flows is, therefore, of crucial importance for protection of water quality. Decreases in water levels due to drought can affect catchment functioning (including partitioning, storage, and release of water), throughout the following year or even for several years if the drought occurs in a larger area. A 1-year drought not only causes water level decreases, but also results in many other changes. When water levels decrease, solutes become more concentrated as the amounts of water decrease in rivers. This pattern is consistent with the results of the present study, as shown by the increase of Mg^{2+}, Ca^{2+}, and Na^+ concentrations during low flow (Table 2). The concentration increase is hypothesized to be associated with evaporation from rivers and the ground surface, as well as the increase of residence and contact of waters with soils during recharge and during discharge of groundwater into rivers (Murdoch *et al.*, 2000; Caruso, 2002). These results demonstrate that water quality degrades under low flow conditions, and in the context of a climate change increase in drought conditions, leads to an increase of at risk situations related to potential health impacts (Delpla *et al.*, 2009).

CONCLUSIONS

Differences in water quality were detected between wet and drought periods but the differences are not the same for each constituent. Climate change resulting in more intense and frequent droughts could cause considerably lower streamflows and consequently have effects on surface water quality, mainly increasing constituent concentrations. In addition, significant differences in water quality can be explained by anthropogenic influences such as land-use changes. Further research should investigate the response of water quality parameters to drought conditions under land use changes and future climate change scenarios.

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