Environ Earth Sci
DOI 10.1007/s12665-012-2182-1

ORIGINAL ARTICLE

Drought impacts on long-term hydrodynamic behavior of groundwater in the tertiary–quaternary aquifer system of Shahrekord Plain, Iran

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Received: 28 November 2011 / Accepted: 4 December 2012

Abstract Shortage of water resources in arid and semi-arid areas causes water supply to be one of the most important subjects and major concerns within NGO and governments' policies in recent years. The Shahrekord Plain aquifer system is located in a semi-arid area and acts as a key source of water supply. Groundwater management in this area is thus very important. Although change in the climatological factors is not possible, long-term fluctuation studies can help in managing the available water resources to overcome from drought or decrease its negative impact. The hydrodynamic study of the aquifer system coupled with the drought indices in each region can be useful in making decisions related to the hydro-ecosystem management of that region. In this article, hydrodynamics of the aquifer system of the Shahrekord Plain coupled with the ratio of P/PET as a drought index, are assessed on the long term. In Shahrekord Plain aquifer, there is a short-term seasonal fluctuation, which is increased by overexploitation during the dry season, when water is needed for irrigation. The hydrodynamic behavior of the plain aquifer on the long term is changing. This fluctuation at first is a function of time. Secondly, it is spatially dependent. Groundwater behavior is directly sensitive to the variation of drought index, both seasonally and on the long term.

Keywords Shahrekord · Drought index · Groundwater level fluctuations

Introduction

Nowadays, one of the most important research subjects is climate change and its impact on water resources. Global warming of the surface temperature by approximately 0.75 °C has been observed over the last 100 years (Trenberth et al. 2007), which resulted in increasing evapotranspiration and water demand, and decreasing precipitation and water resources. Lack of, development of, and wasteful uses of water are fundamental causes of many problems of desertification and environmental degradation (Sharma 1998). Perhaps, the most general of the proposed definitions of drought is the one formulated by Beran and Rodier (1985): "drought is a decrease of water availability in a particular period and over a particular area" (Tsakiris and Vangelis 2004). Identifying drought conditions are necessary for water resource management, especially in arid and semi-arid areas. Several methods were used to recognize drought in a catchment. In each method, different effective climate factors are applied to define an index. By comparison of the index on the long term, the evaluation of climate changes and drought occurrence in any region is possible. When focusing on the hydrological cycle, general circulation models are too coarse to provide regional and local details of the climate at a spatial scale suitable for climate change impact studies (Bronstert 2004). Different downscaling methods have been developed to overcome this problem, dynamically, empirically or these two techniques in combination (e.g. Giorgi et al. 2001). The United Nations Educational, Scientific, and Cultural Organization (UNESCO 1979) developed a classification of climate regimes on the basis of the ratio of mean annual precipitation (P) to potential evapotranspiration (PET) according to the Penman formula, which requires data that are not easily found in most regions of

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the world. This leads the UNEP (1992) to propose a similar climate classification, whereby the Thornthwaite (1948) PET calculation was used instead of Penman formula. This resulted in the following climate classification, for different values of P/PET: hyperarid (<0.05), arid (0.05–0.2), semi-arid (0.2–0.5), dry subhumid (0.5–0.65), and humid (>0.65). In this research, monthly, seasonal and yearly P/PET was applied as a drought index. Indeed, this ratio is not only determining groundwater recharge, but, moreover, in drier conditions, with low P/PET, water demand for agriculture, domestic and other needs are increase, and so P/PET is also suitable as an indicator of groundwater exploitation. Hydrodynamic assessment is one of the most important aspects in aquifer system analysis. The study of the hydrodynamics of the system coupled with the climate regimes in each region can be useful in making decisions for the hydro-ecosystem management of the region (Radfar 2009). This study focuses on the drought impacts on long-term hydrodynamic behavior of groundwater in the tertiary–quaternary aquifer system of Shahrekord Plain, Iran.

The study area

The Shahrekord Plain, covering about 650 km^2, forms part of the Shahrekord Basin with 1,211 km^2, and is located in the northeast of Charmahal and Bakhtiari province in the west of Iran (Fig. 1). The study area is surrounded by mountains with different elevations (Fig. 2). Because of differences in structure, lithology and resistance of mountains against erosion, different levels of mountains have been formed. The highest point is in the south-west of the study area, where the Jahan-been mountain has 3,328 m above mean sea level (m.a.m.s.l.).

According to erosivity of mountains and rate of stream flow, alluvial sediments were deposited in Shahrekord Plain. Approximate slopes are 2/100 in the north, 5/1,000 in the central part and 2/1,000 in the southwest parts. The highest and lowest points in the plain itself are in the northwest and south (at the outlet) of the study area with levels of 2,300 and 2,030 m.a.m.s.l., respectively.

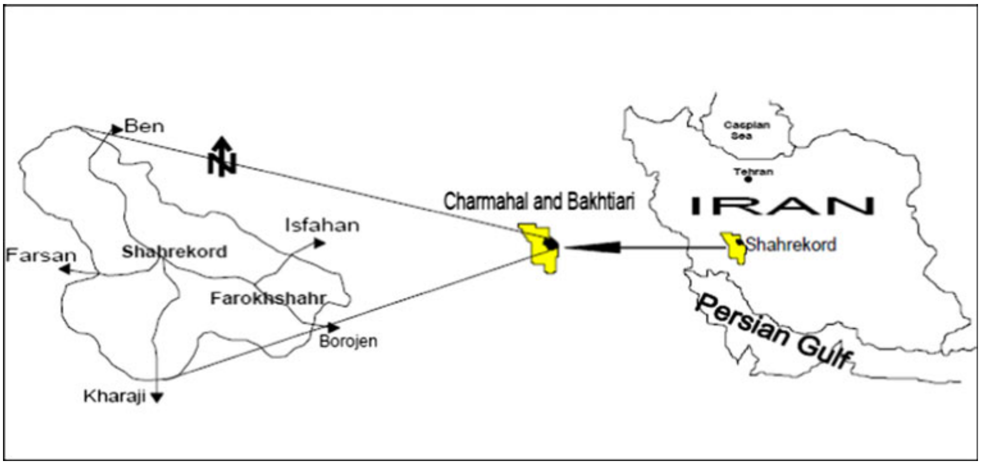
The tertiary–quaternary aquifer system of Shahrekord Plain mainly consists of deposits eroded from surrounding mountainous areas, which are deposited during ages in the plain. Lithologically, this aquifer principally consists of gravel, sandstone, and siltstone. The aquifer is overexploited as a main resource of water for agricultural, drinking, industrial and municipal purposes, particularly during the last 30 years.

Climate

Table 1 displays the long-term (1956–2005) meteorological parameters in the Shahrekord Plain. The long-term mean monthly temperature varies from −1.5 °C in January to 24 °C in July. In addition, the mean maximum and minimum temperature vary from 4.8 °C in January to 34 °C in July and from −7.9 °C in January to 14 °C in July, respectively. This means that the absolutely coldest and warmest months in the study area are January and July. Wind speed in the study area ranges from 1.2 knot in January to 3.5 knot in March and April. Wind speed has more effect on water management during the summer.

Sunshine varies from 184 h in January to 349 h in June. The length of shining is very important especially during the summer because it affects the amount of evapotranspiration. Normally agricultural activity in the study area starts in April and continues to September when sun shining time is high. This causes agricultural water requirements that should be supplied from the groundwater reservoir, which is the only available source in the study area. Distribution of long-term mean monthly precipitation during the year varies from 0 mm in

Fig. 1 Schematic map of Iran. Location of Charmahal and Bakhtiari Province and the study area



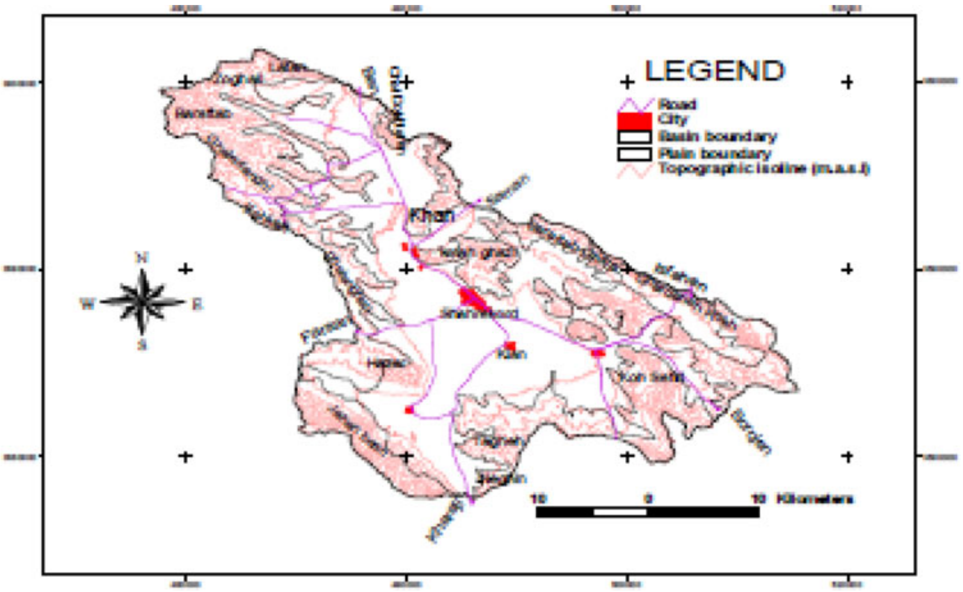


Fig. 2 Shahrekord Plain surrounded by different mountains

Table 1 Long-term (1956–2005) mean monthly precipitation, maximum, minimum and average monthly temperature, maximum and minimum relative humidity (RH), wind speed and sunshine in the study area

Factor/month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yearly
Precipitation (mm)	60.8	47.9	60.3	37.5	14.1	0.9	1.9	0.4	0	6.9	32.2	58.6	321.5
Max T (°C)	4.8	7.6	12.6	18.6	24.6	31.1	34	33.3	29.7	22.9	15	8.6	20.2
Average T (°C)	−1.5	1.2	6	11.3	15.9	20.7	24	23.1	18.8	13.2	7.4	2.2	11.8
Min T (°C)	−7.9	−5.1	−0.6	4	7.2	10.3	14	12.9	8	3.4	−0.3	−4.3	3.5
Max RH (%)	83	82	78	72	66	54	48	48	51	63	75	82	67
Average RH (%)	67	67	62	55	48	42	33	31	32	42	54	63	46
Min RH (%)	48	43	36	31	25	19	20	20	20	26	34	42	30
Wind speed (knot)	1.2	2	3.5	3.5	3.1	2.2	2.3	2	1.7	1.9	1.7	1.6	2.2
Sunshine (h)	183.9	202.5	224.7	232	303.3	349.2	339.8	333.5	312.4	276.3	211.6	188.5	3157.7

September to 60.8 mm in January in the central plain. The long-term annual average of precipitation in the central study area is 321.5 mm. There are two regimes: the dry season, starting from April to September, while the rest of the year is wet. The climate in the study area is semi-humid or semi-dry depending on the classification method.

Materials and methods

Drought in the study area

To assess drought impact on the behavior of the groundwater in the Shahrekord Plain aquifer, different periods of water years have been recognized, based on the available data for water years 1984–1985 to 2003–2004. Then the analysis of the climate regime over this period has been done, on the basis of a comparison of precipitation and potential evapotranspiration.

Precipitation

Precipitation is a major component of the hydrologic cycle. The long-term (October 1984–October 2004) monthly precipitation in the Shahrekord synoptic station is retrieved from the web site of the Chaharmahal and Bakhtiari administration (2008).

Potential evapotranspiration (PET)

The other major factor in the hydrological cycle is potential evapotranspiration. The factors affecting PET are climatic parameters. Therefore, PET is a climatic parameter and can be computed from weather data. Apart from the site location (latitude, longitude and altitude of the station), most PET calculation methods require air temperature, radiation, wind speed and humidity data for daily, weekly, 10 day or monthly calculations. A large number of more or less empirical methods have been developed over the last 50 years by numerous scientists and specialists worldwide to estimate PET from different climatic variables. In 1961, a method of PET estimation was proposed by Hamon, in which PET is function of mean monthly temperature and hours of daylight. The “ETo calculator” program (FAO 2008) offers the possibility to estimate PET with the four methods published in the FAO Irrigation and Drainage Paper No. 24 ‘Crop water requirements’ (Doorenbos 1977), with the Hargreaves equation (Hargreaves 1982), and with the FAO Penman–Monteith equation published in the FAO Irrigation and Drainage Paper No. 56 (Allen 1998). Potential evapotranspiration fluctuates mostly due to variations in the temperature and humidity of the air, with higher evapotranspiration rates on warmer, drier days. Potential evapotranspiration has daily, monthly and seasonal variations. In regions with strong seasonal climate variations, the rate of evapotranspiration is generally lower in winter than in summer because less water can evaporate into cool air than into warm air; where, winters are cold enough for snow and ice, there is very little evapotranspiration during winter.

Monthly air temperature and daylight data were taken from a synoptic station situated in the central part of the study area—the Shahrekord synoptic station—from 1984 (start of piezometric measurements) to 2004 (starting time of analysis). Using Hamon equation (Hamon 1961) monthly, seasonal and yearly PET has been calculated for the Shahrekord synoptic station as PET for the Shahrekord Plain. For instance, Table 2 shows the results of mean monthly PET calculated by the Hamon method for Shahrekord synoptic station in the year 1984, using mean monthly climatological data. As shown in Table 2, due to variations in monthly climatological parameters, including temperature and daylight, monthly evapotranspiration rates are variable in the range from 15.6 mm month^{-1} in December to 114.1 mm month^{-1} in July. Owing to strong seasonal climate variations, the rate of evapotranspiration in the summer (June–August) is highest, while during winter (January–March), it is lowest.

Overview of monitoring network and observation data

In the study area, the groundwater monitoring network involves 31 piezometric wells at different depths, equipped by casing tube, cement foundation and bung (cap) (Radfar 2009). Distribution of piezometric wells in the study area is shown in Fig. 3. At first, a piezometer network including 15 locations were drilled and installed in 1984, while in 1987 four more piezometric wells were drilled to be used for a pumping test investigation. To improve the piezometric network in the study area, another 12 piezometric wells were installed and equipped in 2002, which, to distinguish them from the old ones, are named N1 to N12 by authors. Table 3 indicates more information about all piezometric wells located in the study area. As illustrated in Table 3, the highest depth is reached in piezometric well 27M-7D, with 110 m (ground surface elevation is equal to 2,151.5 m.a.m.s.l.), in the east part of the study area. The smallest depth is related to the piezometric well 24K-31D, with 17.5 m, where ground surface is 2,056.5 m.a.m.s.l., in the west part of the study area. The piezometric network has been completed during time especially in the central part. However, it seems that in the margins, the piezometric network still needs to be completed. Until now, piezometric measurements have been done periodically by water level meter at almost the middle of each month. Long-term analysis of observation data in the Shahrekord Plain has been done using the 19 older piezometers.

Table 2 The estimates of mean monthly PET from the mean monthly climatological data by the Hamon equation in the year 1984

Month	T_{mean} °C	Sun shine (h)	PET mm/month
January	0.4	198.1	15.8
February	2.2	194	18.2
March	7.2	175.3	32.4
April	12.3	226.6	50.7
May	13.4	285.9	63.6
June	20.3	342.6	100.3
July	22.3	294.9	114.1
August	23.5	301.7	110.3
September	17.8	304.9	64.1
October	10.6	261.5	35.8
November	7.3	170.1	24.1
December	1	177	15.6

Time series of piezometric measurements

A sequence of values of a particular variable collected over a time period is a time series. A time series can be composed of a quantity observed at discrete times, averaged over a time interval, or recorded continuously with time (Haan 1977). The evaluation of hydrodynamics with time is studied by time series. Consideration of the behavior of the groundwater and its long-term trends are important to investigate old and recent potential of underground reservoirs to make decisions for the future for a given aquifer system. To distinguish yearly and multi-yearly variations of groundwater levels in Shahrekord Plain aquifer, seasonal smoothing is essential. Moving averages are one of the most popular and easy to use tools available to the technical analyst. Moving averages smooth a data series and make it easier to spot trends. This can be especially helpful in data which strongly vary during time. One of the most frequently used methods for smoothing a time series is the method of the simple moving average (Alizadeh 1999; Fox 1975). Using number of orders is depending on the fluctuation of

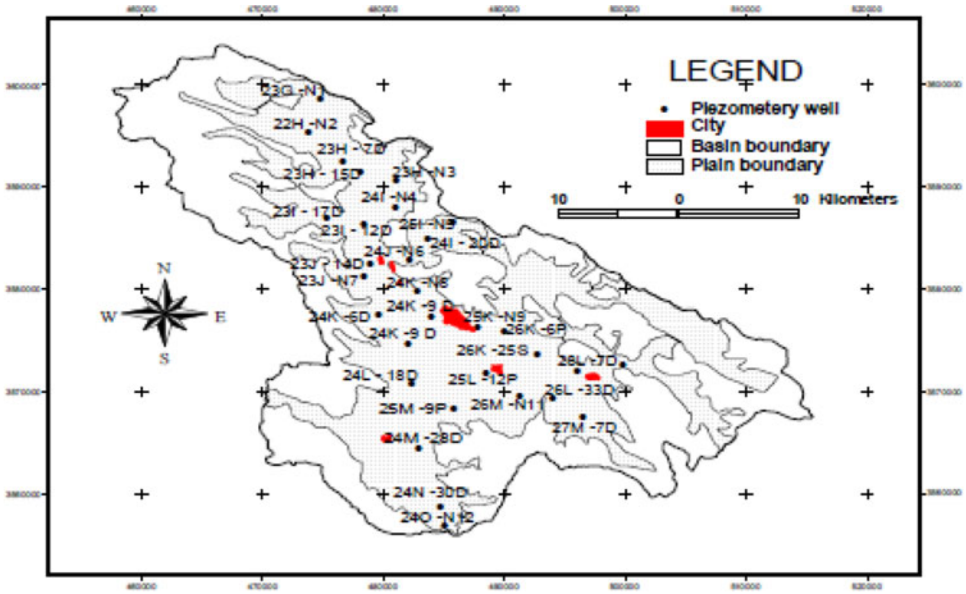


Fig. 3 Location of piezometric wells in the study area

data. To smoothen the monthly and seasonal effects on groundwater fluctuations, a simple moving average of 12th order is applied in Shahrekord Plain aquifer as:

$$\bar{h}_{12\text{sma}} = (h_i + h_{i-1} + h_{i-3} + \cdots + h_{i-11})/12$$

where $\bar{h}_{12\text{sma}}$ is 12th order simple moving average of groundwater level, h is groundwater level of 12th order, h_{i-1} is groundwater level of first backward order and h_{i-11} is groundwater level of 11th backward order.

Results and discussion

Variations of drought index

The ratio P/PET was adopted as a drought index in this study. It has been calculated on a monthly, seasonal and yearly basis for a 20 years period from October 1984 to 2004. The assessment was done on the basis of water years, spanning from the start of the wet season (October) until the end of the next dry season (September of the next year). Table 4 shows the amounts of yearly P/PET during water years 1984–1985 to 2003–2004.

As shown in Table 4, on the basis of UNEP climate classification, the study area is characterized as dry subhumid with long-term yearly P/PET equal to 0.52, while several years fall within the semi-arid class as shown in Fig. 4. Yearly precipitation is not so high, while yearly evapotranspiration is very high, leading to the need for good management of the main water resource in the study area. The driest water year (in terms of precipitation) during the period of 1984–1985 to 2003–2004 has occurred in 1999–2000, while the wettest year occurred in 1991–1992. As shown in Fig. 4, dry years with yearly P/PET less than average occurred in 1984–1985, 1988–1989, 1990–1991, 1993–1994 up to 1994–1995 and 1998–1999 up to 2000–2001. Maximum P/PET is recorded during winter time (December–February), when the precipitation is high and evapotranspiration is low. The maximum monthly ratio of P/PET during 1984–1985 to 2003–2004 is equal to 7.4, while the minimum ratio mostly belongs to the summer months when precipitation is zero, but evapotranspiration is very high. The minimum P/PET in the dry season ranges from 0 to 0.27 and the average value is equal to 0.096, while the maximum P/PET in the wet season ranges from 1.19 to 3.67 and the average value is equal to 1.96 (Table 4). As shown in Fig. 5, the minimum value of the sum of all monthly P/PET values over a water year belongs to the semi-arid year 1998–1999, while the maximum value equal to 31.4 belongs to the humid year of 1991–1992. An apparent difference between yearly P/PET (Fig. 4) and P/PET in the wet season, as well as the sum of all monthly values (Fig. 5), is observed for the years 1996–1997. Despite rather high yearly P/PET, the P/PET for the wet season and the sum of all monthly P/PET values are comparably low, indicating a non-negligible part of precipitation is falling in the dry season, thus not contributing to groundwater recharge, which is reflected in the falling groundwater levels. As such, P/PET for the wet season and the sum of all monthly P/PET values over a water year are better indicators for groundwater level fluctuations. P/PET indices are discussed further with groundwater level fluctuations in the next section.

General trends of groundwater level

The long-term (general) trends can reflect the gradual natural or anthropogenic changes that are occurring in the system over time. To determine the influencing processes

Table 3 Some characteristics of piezometric wells in Shahrekord Plain

Code	Well depth (m)	Installation year	Piezometric level in October 1987 (m.a.m.s.l.)	Piezometric level in October 2004 (m.a.m.s.l.)	Drawdown from October 1987 to October 2004 (in m)
22H-N2	64.5	2002	–	2,153.75	–
23G-N1	63.0	2002	–	2,148.19	–
23I-17D	59.8	1984	2,121.82	2,110.66	11.16
23H-7D	–	1987	2,128.65	2,125.96	2.69
23H-15D	53.4	1984	2,115.07	2,112.05	3.02
23I-12D	64.5	1984	2,093.93	2,090.75	3.18
23J-N7	49.5	2002	–	2,063.10	–
23J-14D	33.8	1984	2,075.11	2,068.04	7.065
24K-6D	57.0	1984	2,052.36	2,041.97	10.394
24I-N4	72.0	2002	–	2,099.39	–
23H-N3	109.0	2002	–	2,107.28	–
24K-31D	17.5	1984	2,048.27	2,030.77	17.5
24J-N6	54.0	2002	–	2,067.57	–
24L-18D	30.0	1984	2,041.63	2,040.07	1.56
24K-N8	84.0	2002	–	2,040.73	–
24M-28D	40.7	1987	2,040.66	2,039.04	1.62
24I-20D	48.2	1984	2,078.62	2,059.42	19.2
24 K -9 D	53.1	1987	2,049.38	2,031.80	17.58
24N-30D	42.1	1987	2,031.48	2,030.60	0.88
24O-N12	51.0	2002	–	2,026.63	–
25I-N5	82.0	2002	–	2,062.57	–
25M-9P	27.0	1984	2,048.70	2,038.93	9.77
25K-N9	59.0	2002	–	2,039.95	–
25L-12P	91.0	1984	2,053.69	2,038.28	15.41
26K-6P	44.5	1984	2,048.25	2,038.04	10.209
26M-N11	92.0	2002	–	2,037.06	–
26K-25S	62.0	1984	2,051.03	2,035.02	16.01
26L-33D	52.8	1984	2,075.35	2,060.72	14.63
27L-N10	101.0	2002	–	2,052.75	–
27M-7D	110.0	1984	2,090.69	2,071.36	19.325
28L-7D	44.4	1984	2,117.32	2,111.20	6.121

on the studied aquifer system, for 19 piezometers out of 31 (total piezometers), long time data series were available and they were studied as shown in Fig. 6. The best fit of linear trends of data for each piezometer (Fig. 6) with corresponding linear equations (as shown in Table 5), is recognized. As shown in Fig. 6 and Table 5, for all 19 piezometers the general water table trend is descending, although its rate is not similar in different locations. Both monthly P/PET and piezometric negative trends show that decreasing precipitation and/or increasing PET as a result of drought in the study area, cause decreasing groundwater table as a direct negative effect. The negative general trend in the system is indicating the mismanagement of the aquifer system of the study area, and is alarming.

The descending trend of water table at the outlet (piezometers 24L-18D, 24M-28D and 24N-30D) is smaller in comparison with the other piezometers. The gradient of water level between the north-west of the plain (piezometer 23H-7D) and the outlet (piezometer 24N-30D) in October 1984 was 104.8 m (2,136.5–2,031.7 m.a.m.s.l.), while the corresponding gradient for October 2004 is 95.36 m (2,125.96–2,030.6 m.a.m.s.l.).

Monthly and seasonal fluctuations

Figure 6 shows the monthly fluctuation of groundwater level in 15 piezometers during water years 1984–2004 and four piezometers during 1987–2004. It shows that groundwater fluctuation between subsequent months is not very

Table 4 Variation of P/PET index in water years 1984–1985 to 2003–2004

Water year	Yearly P/PET	Climate class (UNEP 1992)	Maximum monthly P/PET	Month of maximum P/PET	Minimum monthly P/PET	Months of minimum monthly P/PET	P/PET for wet period (October–March)	P/PET for dry period (April–September)	Sum of monthly P/PET	Main change in groundwater level
1984–1985	0.25	Semi-arid	2.8	Dec	0	Jul–Sep	1.41	0.02	10.01	↓
1985–1986	0.58	Dry subhumid	5.08	Dec	0	Oct–Jun–Jul–Sep	1.62	0.27	13.91	
1986–1987	0.53	Dry subhumid	7.5	Dec	0	Jun–Sep	2.67	0.09	20.76	↑↑
1987–1988	0.66	Humid	5.3	Dec	0	Jun–Sep	2.45	0.05	16.66	
1988–1989	0.39	Semi-arid	4.4	Jan	0	Oct–Jun–Sep	1.74	0.06	14.97	
1989–1990	0.56	Dry subhumid	6.7	Dec	0	Jun–Aug–Sep	2.18	0.04	18.69	
1990–1991	0.44	Semi-arid	3.4	Jan	0	May–Jul–Aug	1.49	0.02	10.46	↓
1991–1992	1.06	Humid	7.4	Jan	0	Jun–Sep	3.67	0.13	31.4	↑↑
1992–1993	0.68	Humid	7	Feb	0	Oct–Jun–Sep	2.5	0.25	21.52	↑↑
1993–1994	0.28	Semi-arid	2.65	Jan	0	Jun–Sep	1.3	0.05	9.13	↓↓
1994–1995	0.29	Semi-arid	7	Nov	0	Jun–Sep	2.09	0.18	15.06	↓
1995–1996	0.74	Humid	5.3	Mar	0	Jun–Sep	2.38	0.16	18.55	
1996–1997	0.58	Dry subhumid	3.9	Mar	0	Jul–Sep	1.41	0.14	10.94	↓
1997–1998	0.53	Dry subhumid	6	Jan	0	Jun	2.47	0.05	19.76	↑
1998–1999	0.27	Semi-arid	3.7	Feb	0	Nov–Jun–Aug–Sep	1.19	0.02	8.8	↓↓
1999–2000	0.29	Semi-arid	2.5	Dec	0	Apr–Jun–Aug–Sep	1.21	0	9.63	↓↓
2000–2001	0.36	Semi-arid	5.4	Dec	0	Jul–Aug	1.47	0.03	10.99	↓
2001–2002	0.79	Humid	7	Dec	0	Jun–Sep	2.2	0.13	19.04	↑↑
2002–2003	0.56	Dry subhumid	4.7	Jan	0	Jun–Sep	2.01	0.08	16.4	
2003–2004	0.61	Dry subhumid	7.4	Jan	0	Oct–Aug–Sep	1.77	0.13	15.65	
Average	0.52	Dry subhumid	5.26		0		1.96	0.096	15.6	

↑, strong rise in groundwater level in wet season; ↑↑, very strong rise in groundwater level in wet season; ↓, strong drop in groundwater level in dry season; ↓↓, very strong drop in groundwater level in dry season

high, but seasonally there is a fluctuation. There is a general sinusoidal behavior in groundwater level for each piezometer during the year. It can be stated that each year can be separated into two regimes: a wet period starting from October to April and a dry period starting from May to September. During the wet period, cultivation in the plain is very low (almost zero) and discharge from the aquifer for agriculture is not taking place, while recharge to the aquifer is happening, which causes rising groundwater tables during October to April. In the dry period, recharge to the aquifer is low (no precipitation), whereas pumping is increased from May onward and reaches to the peak amount in September while groundwater table is at minimum. Fluctuating groundwater levels are indicated in Fig. 6, together with the monthly drought index P/PET.

Amplitudes of seasonal fluctuation for each water year are different for different piezometer locations, and depend on the climatological factors (precipitation and evapotranspiration), lithology and geological structure and/or distance to recharge and discharge sources. As

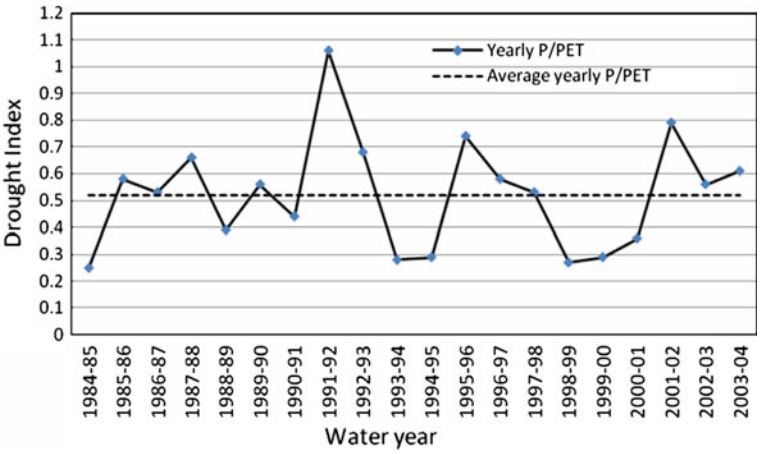


Fig. 4 Yearly P/PET variation on the long term (1984–1985 to 2003–2004)

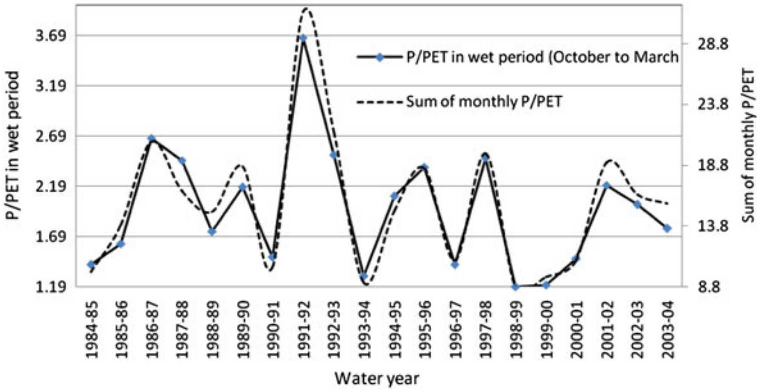


Fig. 5 Variation of "sum of monthly P/PET" and "P/PET in wet period" on the long term (1984–1985 to 2003–2004)

demonstrated in all graphs, because of the high ratio of P/PET in wet periods of water years 1991–1992 to 1992–1993, the absolute maximum groundwater table was recorded in all piezometers for these years. However, the absolute minimum did not occur everywhere at the same time.

Yearly and multi-yearly fluctuations

The 12th order simple moving average for all 19 piezometers has been shown in Fig. 6. By paying attention to the behavior of smoothing graphs, the absolutely highest groundwater levels were recorded in the whole study area in 1992–1993, while the absolutely lowest levels were found in 2000–2001 in the north-west and at the outlet, whereas in the central part, lowering of levels was continued till 2003–2004. Generally for multi-year fluctuations in the study area, it can be judged that water year 1984–1985 showed very low level, while 1985–1986 to 1987–1988 were moderate and then 1988–1989 to 1990–1991 showed again low levels. After that, 1991–1992 to 1992–1999 showed high to moderate levels, however 1999–2000 to 2000–2001 showed low groundwater levels. From 2001–2002 to 2003–2004 in the north-west and at the outlet, a moderate period was maintained, while in the central part the groundwater levels remained low. Climatological factors, such as precipitation and influencing factors on evapotranspiration all affected water levels in the study area as shown in Fig. 6, besides the effect of pumping.

Subdivision of plain into different zones based on piezometric behavior

Return flow and the influence of the drainage system accompanied with recharge are influencing, the aquifer system in some parts. For instance in the outlet area (e.g. 24N-30D and 24M-28D), fluctuation is not so high, since the aquifer system in this area is influenced by surface drainage and groundwater movement from all directions to the outlet, plus karst recharge from the margins and from Jahan-been Mountains.

In the central part, because of overexploitation, piezometric water level is going down continuously till 2004.

The variation of the water level in different piezometers in the study area is a function of different factors:

1. climatological factors (dry and wet periods affecting the whole area);
2. anthropogenic factors (high abstraction in the central plain);

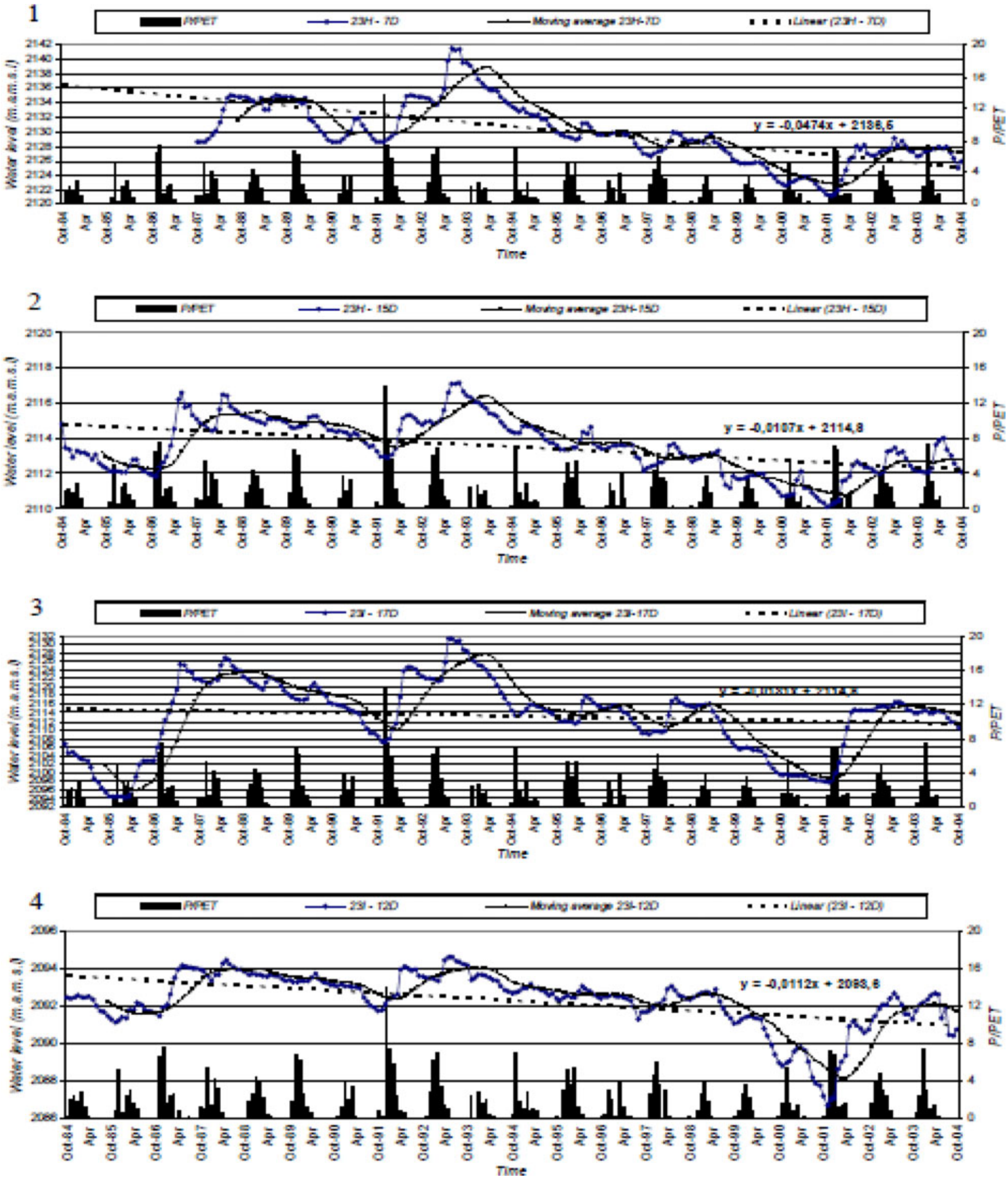


Fig. 6 Long-term monthly groundwater level fluctuations, general trends, 12th order moving average of 19 piezometers (from 1 to 19) and the monthly ratio of P/PET in the study area

3. geological and lithological conditions (different aquifer characteristics influencing the amplitude of fluctuations in different places in the same period);
4. location of piezometers compared to the recharge area (karst mountainous aquifer) and to the discharge area (the outlet).

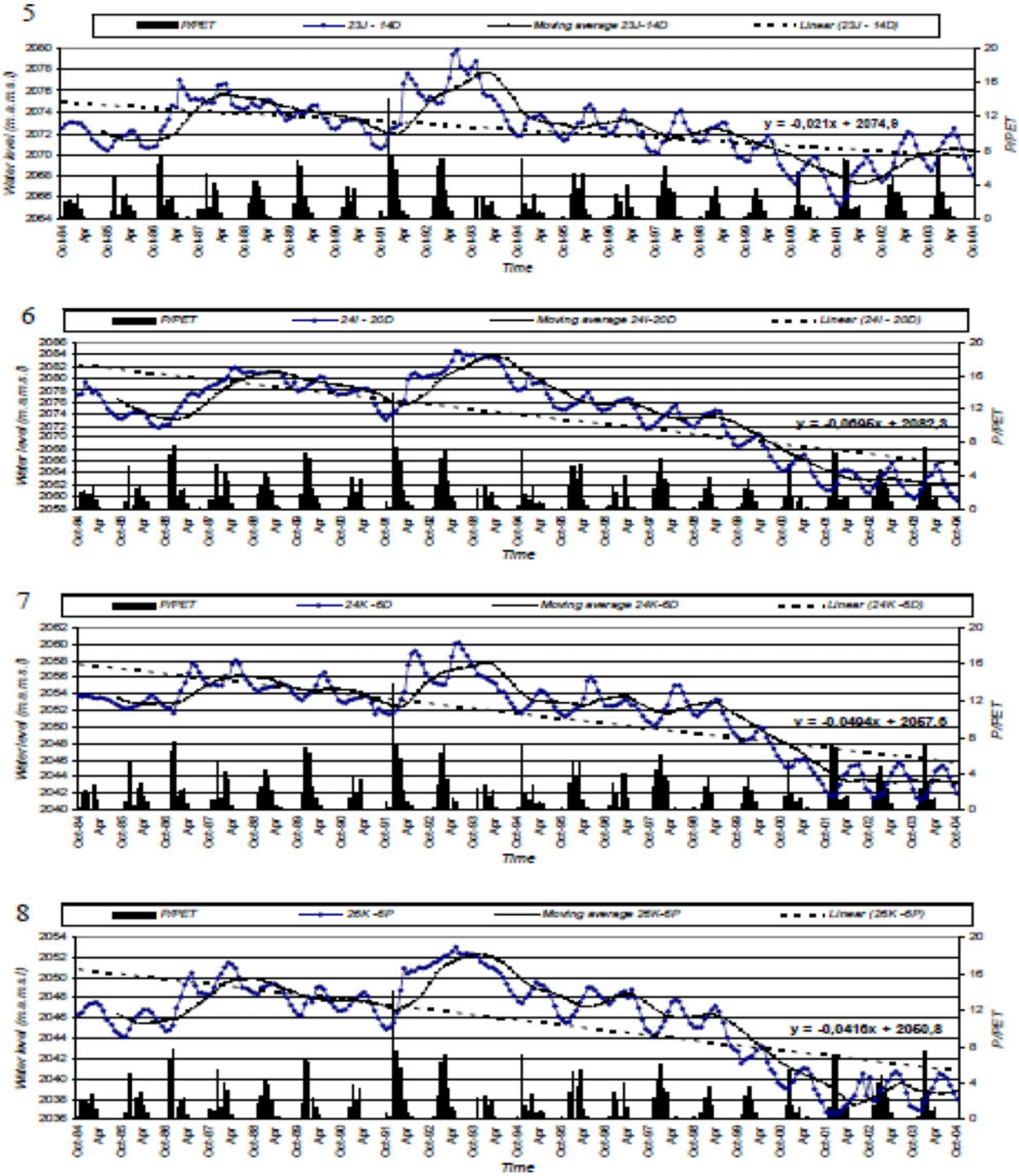


Fig. 6 continued

On the basis of the above-mentioned factors, the time series of piezometric measurements have been evaluated, and piezometers with similar trends were grouped together. On this basis the study area was divided into three zones (Fig. 7). The average of groundwater level for each zone is calculated using related piezometers occurring in that zone. The time series of average piezometric level for each zone from October 1984 to

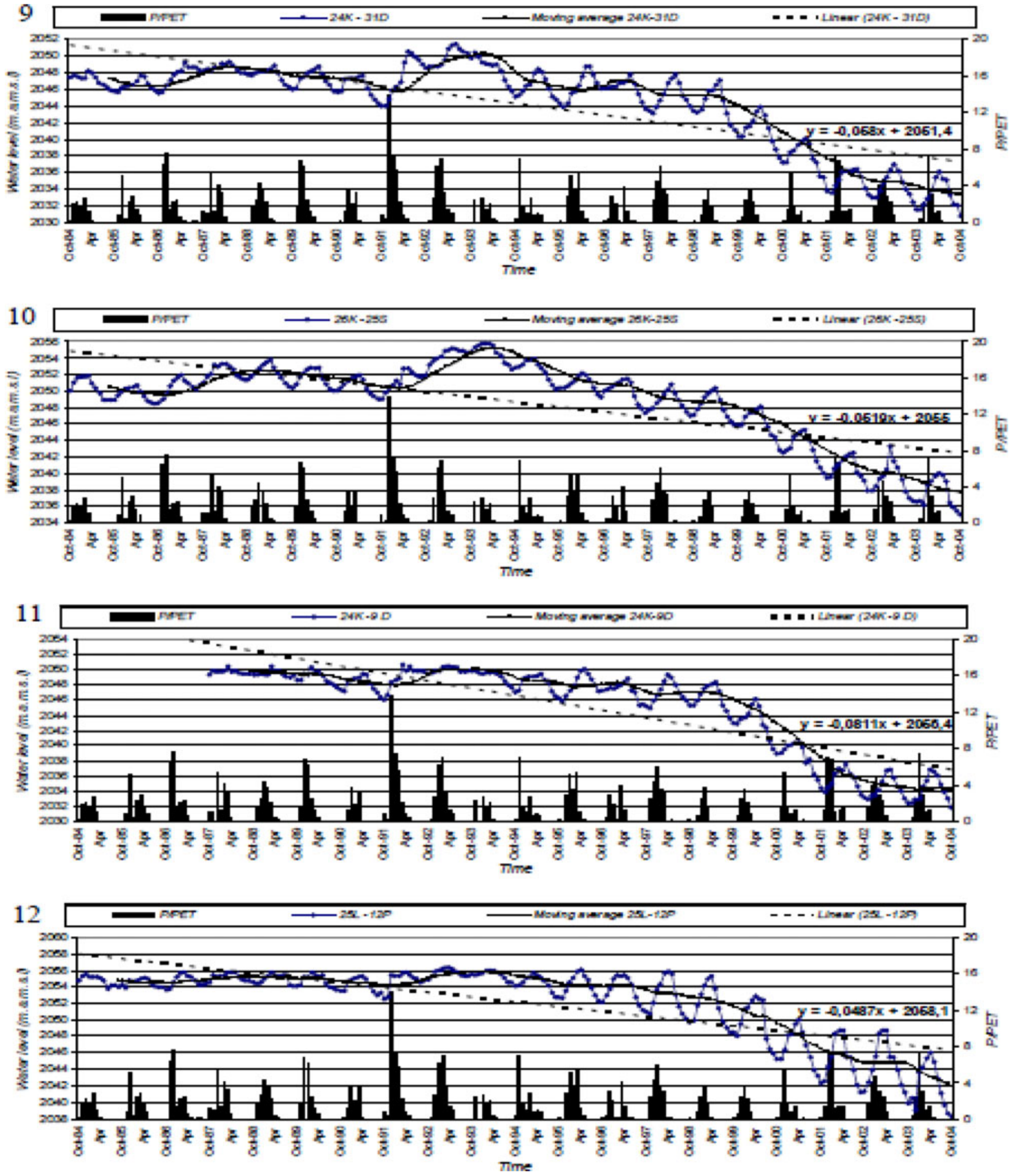


Fig. 6 continued

October 2004 and monthly P/PET are shown in Figs. 8, 9 and 10. For zone 2, a different vertical scale was used compared to zones 1 and 3, because of the restricted variations in groundwater level in the outlet area. Comparison of time series of the three zones shows, that maximum groundwater fluctuation occurs in zone 3 (central plain) and zone 1, while the minimum variation occurs in zone 2 (outlet). Zone 1 is far from the central

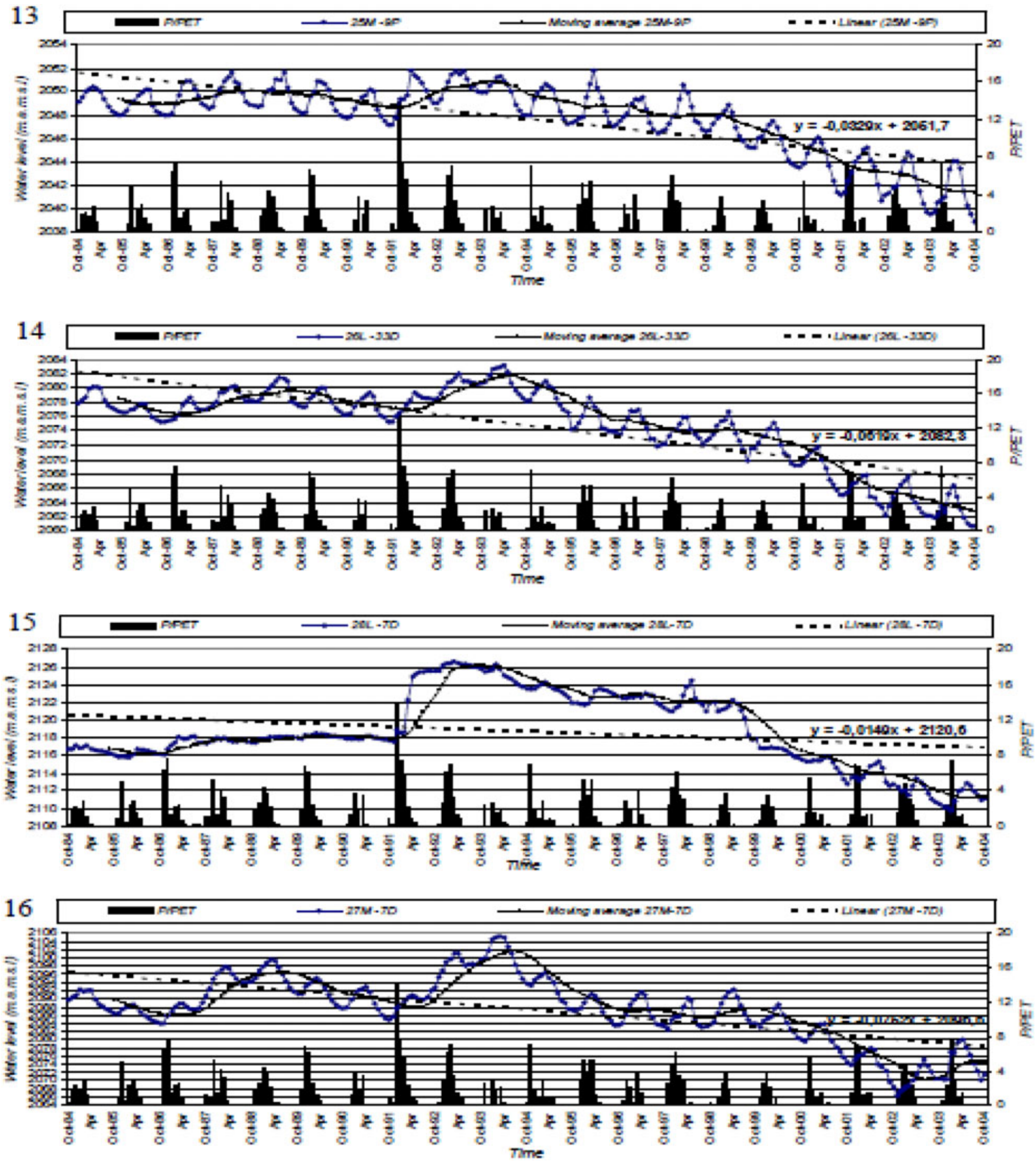


Fig. 6 continued

plain (zone 3) and groundwater exploitation in that zone is lower than in the central plain. However, as a result of the limited aquifer thickness in this zone, the direct impact of meteorological variations on the groundwater level is stronger.

Relation between different P/PET drought indices and groundwater level fluctuations

By paying attention to monthly P/PET in Figs. 8, 9, and 10, it is clear that during winter and spring (wet period)

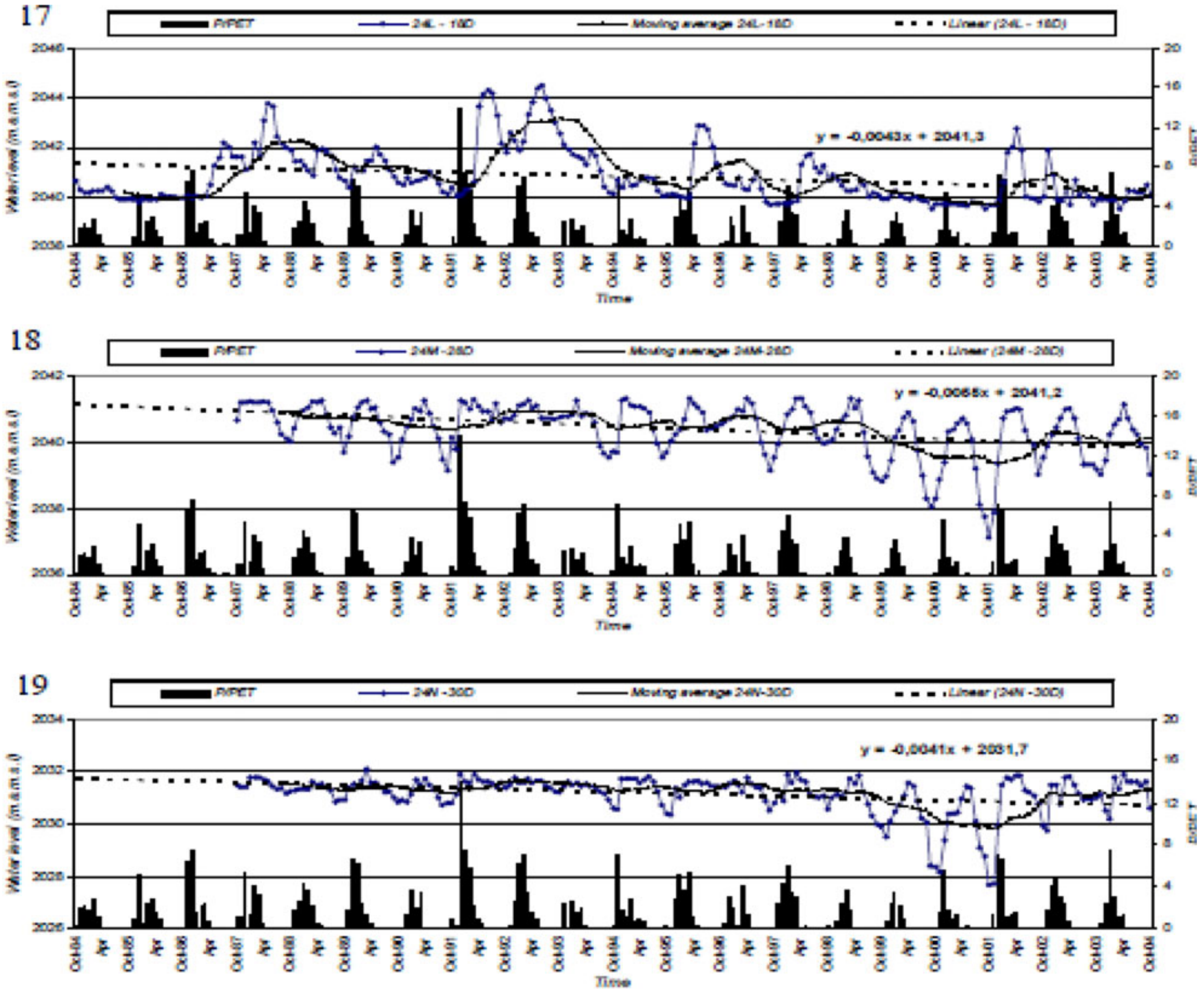


Fig. 6 continued

drought index is high and groundwater level is raised, while in summer and fall (dry period), the P/PET drops to zero and groundwater level is declining. For instance in the dry years 1990–1991, when P/PET for the wet period is 1.49 and the sum of monthly P/PET is 10.46, the decline of groundwater level in zone 1 is 2.7 m, in zone 2 it is 2.4 m and in zone 3 it is 3.58 m. Whereas in the subsequent wet year 1991–1992, when P/PET for the wet period is 3.67 and the sum of monthly P/PET is 31.4, the average rise of groundwater level in zone 1 is 6.54 m, in zone 2 it is 2.25 m and in zone 3 it is 5.31 m. Important groundwater level fluctuations (apart from average yearly fluctuations) have been indicated in Table 4. It can be observed that strong rises of groundwater table are associated with values of the sum of monthly P/PET above 19, while values higher than 20 correspond with sharp rises. On the other hand, values below 11 correspond to important drops in groundwater level, while dramatic drops are characterized by values below 10. This drought index, the sum of monthly P + PET values over a hydrological year, seems to be the best indicator for groundwater level fluctuations, as it accumulates P/PET values that were assessed on the monthly basis. P/PET for the wet season also comprises this information (groundwater recharge is expected to occur during the wet period). Marker values for this indicator are 2.4 (2.5) as lower limits for rising water table and 1.5 (1.4) as upper limits for dropping water level. This indicator seems to correlate a little less with main water table fluctuations (compared to the sum of all monthly P/PET), probably because the actual extent of dry periods is variable from year to year, which was not accounted for in the calculations.

Figures 8–10 show that zone 1 is more influenced by drought then zone 3 and ultimately zone 2, due to the limited aquifer thickness in this upstream zone. Due to overexploitation, continuous declining of groundwater level in

Table 5 General trend coefficients of linear equation $y = A + B\,x$ for different piezometers

Piezometer	*A*	*B*
23H-7D	2,136.5	−0.0474
23H-15D	2,114.8	−0.0107
23I-17D	2,114.8	−0.0131
23i-12D	2,093.6	−0.0112
23J-14D	2,074.9	−0.021
24I-20D	2,082.3	−0.0695
24K-6D	2,057.6	−0.0494
26K-6P	2,050.8	−0.0416
24K-31D	2,051.4	−0.058
26K-25S	2,055.0	−0.0519
24K-9D	2,056.4	−0.0811
25L-12P	2,058.1	−0.0487
25M-9P	2,051.7	−0.0329
25L-33D	2,082.3	−0.0619
28L-7D	2,120.6	−0.0149
27M-7D	2,096.6	−0.0752
24L-18D	2,041.3	−0.0043
24M-28D	2,041.2	−0.0055
24N-30D	2,031.7	−0.0041

zone 3 from 1994–1995 up to 2003–2004 takes place; this factor is superposed onto the climatological factor, the latter which is indicated by the drought index.

Conclusion

The hydrodynamic behavior of the plain aquifer on the long term is changing. This fluctuation at first is a function of time. Secondly, it is spatially dependent. Meteorological and climate changes, and the high abstraction from the aquifer are changing the aquifer behavior. In Shahrekord Plain aquifer there is a short-term seasonal fluctuation, which is increased by overexploitation during the dry season, when water is needed for irrigation (negative trend). During the wet period there is a recovery of groundwater levels. There is a long-term decreasing trend, especially in the central plain, where overexploitation occurs because of the high demand for groundwater as a main water resource in the study area. The climatological influence on groundwater level fluctuations in the plain is important. It can be observed that strong rises of the groundwater table are associated with values of the sum of monthly P/PET over a hydrological year above 19, while values higher than 20 correspond with sharp rises. On the other hand, values below 11 correspond to important drops in groundwater level, while dramatic drops are characterized by values below 10. This drought index, the sum of monthly P/PET values over a hydrological year, seems to be the best indicator for groundwater level fluctuations, as it accumulates P/PET values that were assessed on the monthly basis. Next to the climatological influence, overexploitation is lowering groundwater levels, especially in zone 3. The aquifer is not in a good condition, especially around Shahrekord city, and continuation of abstraction at this rate or more, is alarming.

Recommendations

The aquifer system of Shahrekord Plain, as a main water resource for municipal, agricultural and industrial uses in the plain, is under high pressure. Decreasing of high

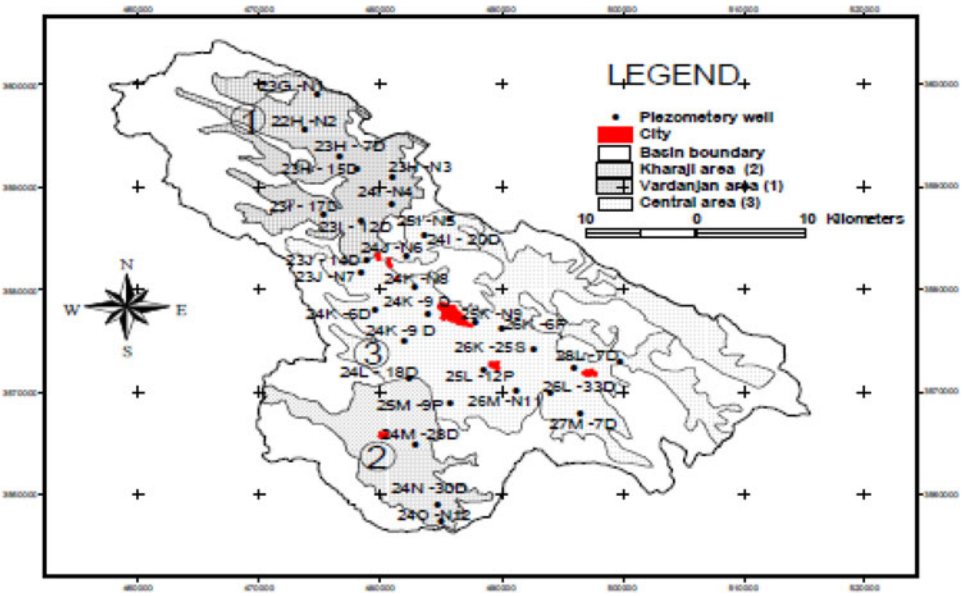


Fig. 7 Subdivision of plain aquifer into different zones with indication of tangent of negative general trend of long-term groundwater level fluctuations

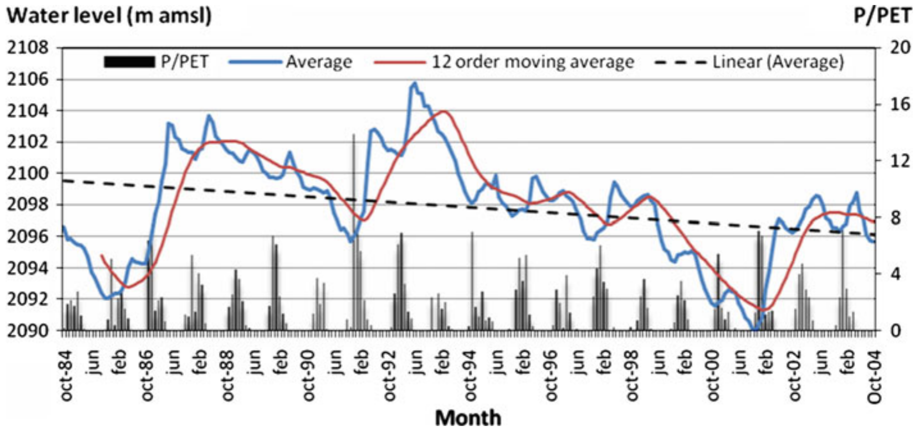


Fig. 8 Long-term monthly groundwater level fluctuations, general trends, 12th order moving average and P/PET in zone 1 of the study area

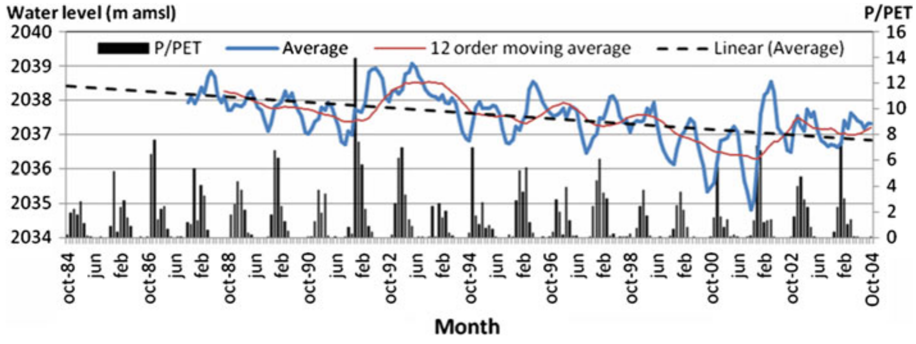


Fig. 9 Long-term monthly groundwater level fluctuations, general trends, 12th order moving average and P/PET in zone 2 of the study area

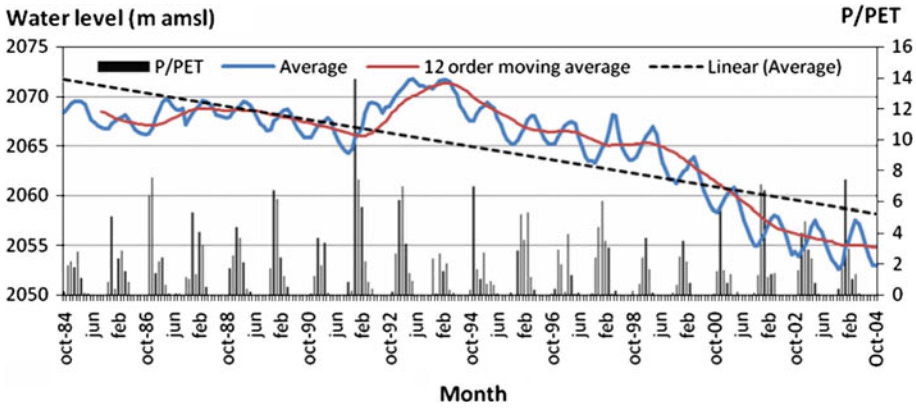


Fig. 10 Long-term monthly groundwater level fluctuations, general trends, 12th order moving average and P/PET in zone 3 of the study area

abstraction, especially around Shahrekord City, is essential. Developing artificial injection projects in the study area can be helpful. In addition, exploring for other water resources for the study area is recommended. Moreover, careful monitoring of the hydrodynamic state of the aquifer is of crucial importance, as a starting point for a good management. Next to the continuation of the existing monitoring programme, we have additional recommendations:

(a) installation of new piezometers, especially in the eastern parts of the aquifer;
(b) developing the piezometric monitoring network into an automatic system.

Acknowledgments We would like to thank the Ministry of Power of Iran and in particular appreciate the Departments of Water and Meteorology in Shahrekord for their support in data collection. The first author would like to thank the Ministry of Research, Science and

Technology of Iran and Shahrekord University for their financial support and Ghent University for accepting him during his PhD research.

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