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Water Crisis Analysis Using GIS; Case Study: Nishabur Plain, Iran

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Abstract: Water crisis as one of the most important environmental hazards has environmental, social and economical impacts. Researchers have adopted different methodologies and approaches including water balance equations, climatic changes effects and land use planning in the study of water crisis. In this study, Geographic Information System (GIS) techniques were employed to analyze the situation of Nishabur Plain (NE of Iran) and discuss the management of water crisis in the study area. For this propose, various data layers including precipitation and evapotranspiration rate, water table and groundwater exploitation, groundwater drowdown, permeability and land use layers were prepared. After weighting the gathered data based on their importance in water crisis with ranking method, GIS overlay function was used to produce the water crisis map. The result of this study indicates that the whole plain is confronting with water crisis of different severity level. The most important factor affecting the existing water crisis is the quality of cultivation for agricultural purposes. So, in order to reduce the gravity of water crisis, the necessity of new administrative strategies including the improvement of some land use classes and the cultivation of species with lower water need was highlighted.

Key words: Water crisis, land use, water resources, hydrology, Nishabur Plain

INTRODUCTION

Life on earth depends on water and it is estimated that only 0.08 of the world's water is obtainable for human consumption (Paul, 2005). Water has recently become part of the international political agenda (Biswas, 2005). The population growth has increased the demand for fresh water for drinking and farming use. Nowadays, water is considered a valuable commodity. The identification of its resources and proper exploitation has become a fundamental necessity. If surface and underground water resources are not properly managed, water crisis will be created with social, political and economical consequences.

Water crisis is caused and increased by various factors which some of the most important ones are: land use change, analyses of water needs of the past and future, review of water balance and its quality (Anonymous, 2000). Therefore, water crisis has been considered from different perspectives. Biswas (2005) believed that major crises are unlikely to come from water scarcity, even if some countries will find it difficult to manage such problems. Iskandar and David (2004) have studied the spatial and temporal variability of water productivity in the Syr Darya in the Central Asia. The results of their study indicated that water availability depends on the kind and size of cotton farms and rice paddies. Ajali and William (2004) studied the water crisis in the Spanish Guadalquiviv River basin and proposed that the main solution lies in the preparation of integrated management policies for water resources at basin scale. Variability of water resources has also been studied in terms of climatic changes such as precipitation, temperature, evaporation etc. Dawen *et al.* (2004) conducted a similar study in Yellow River, China and concluded that irrigation conditions in China are directly influenced by the amount of rainfall and evaporation. As a result, in timespans experiencing more precipitation and less evaporation, better irrigation will become possible. Ferrett and Robert (1983) also studied the effects of farming land use planning on the quality of underground water. They focused on the roles of pesticides in the contamination of underground water and proposed appropriate planning policies for the prevention of such issues.

The study of water crises has also been conducted for different countries located in arid zone such as: in Yemen by Almas and Scholz (2006), in Gaza strip by Weinthal *et al.* (2005), in Kuwait by Darwish and Al-Najem (2005), in Mediterranean region by Araus (2004) and in Pakistan by Faruqui (2004). Some studies were also

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carried out in humid areas such as western Prairie Provinces of Canada by Schindler and Donahue (2006).

Iran is located in arid zone of the world and therefore annual variation of rainfall is the main problem which is known as the major factor of water crises in different geographic regions of the country. The water crises have had cultural, political and ethical dimensions in Iran (Foltz, 2002). Countries like Iran whose economy is dependant on agriculture should give due attention to water resources management since more than 70% of available water resources are used for farming purposes (Anonymous, 2001). Considering the quality and quantity of the exploited water and the way it is used in agricultural activities, its direct and indirect effects on water resources is observable. The lack of proper use of land, salinization and desertification are some of the environmental impacts, especially in arid areas which experience shortage of water.

Water crisis in Nishabur Plain has become grave since 1984 after the hydrological imbalances created by over-exploitation of water resources. If the overuses of the available water resources and the negative water balance continues, water crisis will end up in the complete deployment of underground reservoirs and all economical investments will be lost.

All above-mentioned researches indicate that water-related issues have attracted many researchers which adopted different approaches to address the problem. The main aim of this study is to apply GIS techniques to water crisis analysis in order to integrate such knowledge in management of water crisis.

MATERIALS AND METHODS

Nishabur Plain is part of Nishabur Kal Shur watershed located in Khorasan province, NW, Iran (Fig. 1). Surface runoffs of the basin originate from the surrounding mountains and after getting to the plain penetrate into the soil and a proportion of as the subsurface water is discharge at Husseinabad Woodland.

The region has an arid to semi-arid climate. Precipitation varies at different parts of the basin and a noticeable variation is observable in the temporal pattern of precipitation amount in recent years, especially in plain areas.

More than 80% of the region's soil is cultivable and gives the area a significant agricultural position in Khorasan Province. More than 70% of the lands are cultivated by grain, industrial products and fruits by using aquaculture which consumes too much water incompatible with the water scarcity in the region.

The farmers of the Nishabur Plain have always been dependant on underground water. The volume and extent of subsurface water utilization varies at different parts of the aquifer. Several factors including high evaporation, low precipitation and its uneven distribution in addition to disorganized drilling of deep wells have caused problems in the water resources of the aquifer. The plain has been witnessing an annual decrease of 0.2 m in underground water level since 1992 (Sadolah, 1991). About 95% of the total 788 million m^3 of the fetched water is used for farming purposes (Anonymous, 2001).

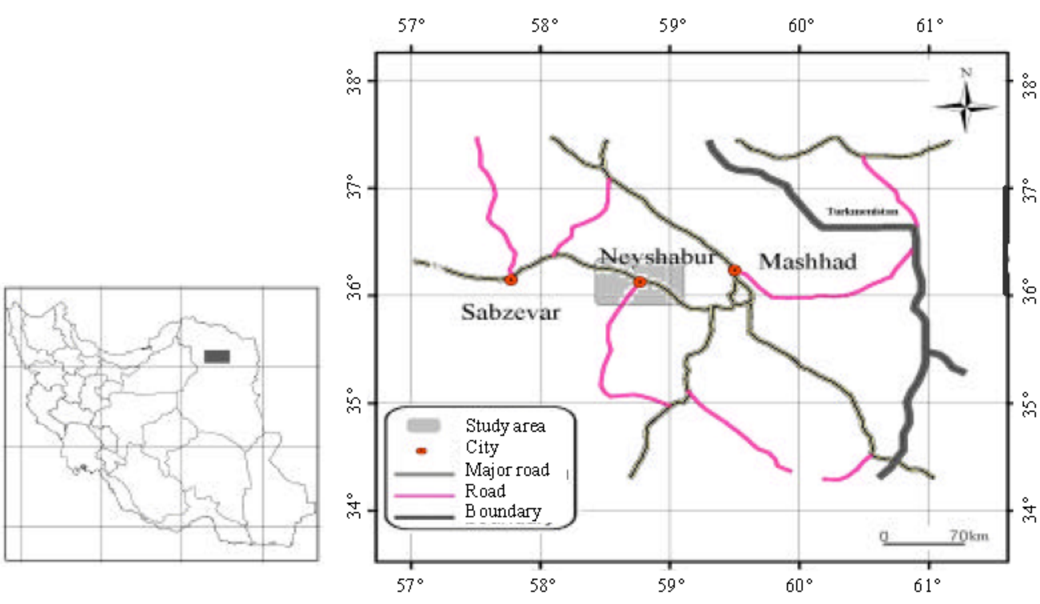

Fig. 1: The location of the study area

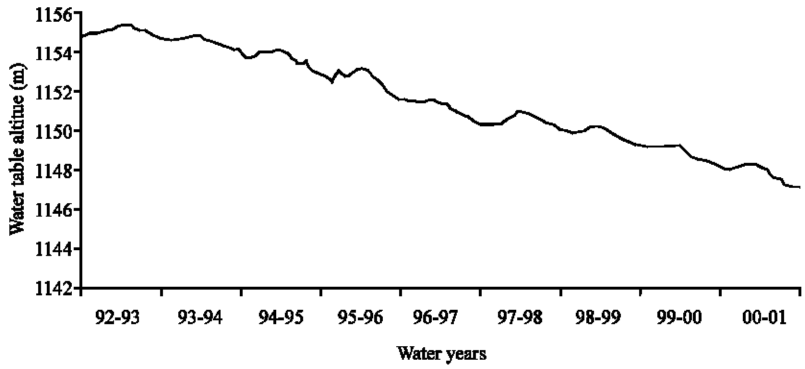

Fig. 2: Groundwater hydrograph of Nishabur plain from 1992 to 2001 water years

The rivers of the region are not that much big and their average annual water discharge is estimated to be approximately 150 million m^3.

Water aquifer in Nishabur Plain supplies about 9.2% of Khorasan water discharge (Saddah, 1991). Taking into consideration the negative water balance (149 million m^3 deficit in reservoir), the Ministry of Energy has announced the Plain as a protected region since 1986. The below hydrograph (Fig. 2) indicates that since the water year 1992-1993, the subterranean water table has been continuously declining in this plain (Toos Ab Consultant Engineer Company, 1998).

To conduct this research, the following statistics and data have been used:

Climatic data: Two main climatic factors namely precipitation and evaporation rate which play a significant role in water crisis have been taken into account in this study for the period of 1990-2001. In this period two climatic map including precipitation and evapotranspiration, were prepared in GIS. The Penman method was used to estimate the evapotranspiration rate (WMO, 1968).

Water table depth: Various required hydrological data was used for the calculation of water balance of the study area. The relevant data items representing the inputs and outputs of surface and subsurface flows into the study area such as the volume of the fetched water from wells and the location of Qanats and springs were extracted from the statistics of Ministry of Energy for the period of 1992 to 2001. In addition, the wells' water level and reduction rate and water exploitation were other important parameters which were used in the temporal analysis of water crisis in Nishabur Plain. Based on the gathered data, water table depth map was prepared using the statistics of current wells in Nishabur plain. The water table has had varied depths Which the nearest to the surface is 10 m and the lowest is 135 m deep located in the southern parts of the basin. Slope gradient of water table is from northern to southern areas in the plain.

Groundwater exploitation rate: Based on precipitation data and surface geological conditions the exploitation rate map prepared by the Ministry of Energy was classified into 5 classes (Table 3).

Groundwater falling rate: Based on the collected data, the water table of the plain is falling 0.2 m annually. The groundwater level lowering is not evenly distributed all over the plain. Nonetheless, all over the plain aquifer, the groundwater level in falling compared to the sea level. Making use of the collected data items, the iso-falling map was prepared for the plain using Inverse Distance Weighting (IDW) interpolation method in GIS (ARCGIS software). The prepared map indicates that water level declining has been more than 20 m during 1992 to the present due to inappropriate use of groundwater by wells.

Permeability map: Due to the lack of relevant data in this area relating to the permeability rate, the given map was prepared by the study of area's geological maps and the classification of different permeability groups showing the approximate permeability of the region.

Land use map: This map was prepared by the analysis of Landsat ETM+ images of 2000. Based on the prepared map, 41.3 and 43.3% of the area belongs to irrigated farming and rangeland, respectively. Other land uses are woodland (10.5%), dry farming (3), bare land (1.3), orchards (0.5 %) and urban area (0.1%).

Considering the areas under irrigation, they constitute about 41% of the study area indicating a strong reliance of the agricultural activities on irrigation which due to low precipitation in the region is supplied by groundwater resources.

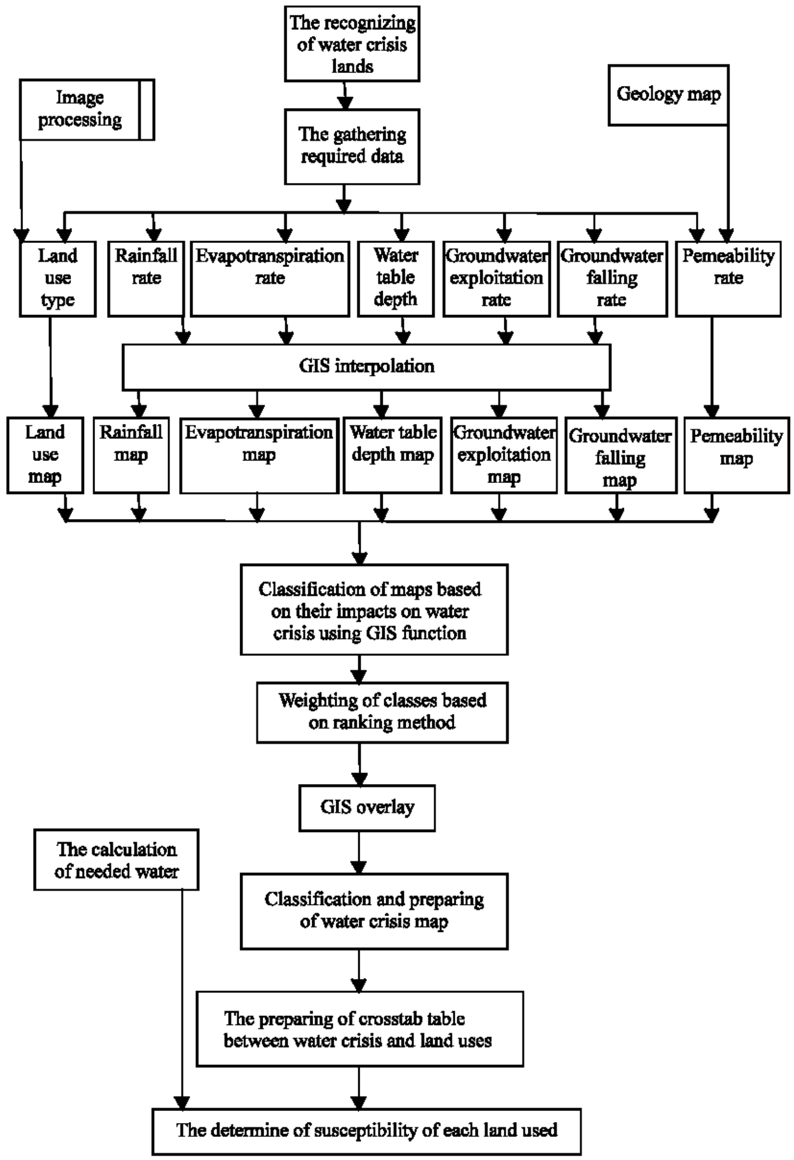

Fig. 3: Flowchart of methodology

The scale of all the maps used and the layers produced were 1:250000 and its database have been obtained in the vector and raster formats in GIS and the relevant spatial analysis were carried out.

The research methodology is shown in the Fig. 3. In the first step the data was converted to related thematic maps. To produce some maps such as rainfall and evapotranspiration maps, GIS interpolation functions were used. Then each of produced maps was classified into different classes in terms of their impact on water resources of the region. Next, each class was given proper weight according to its impact and significance. These classes were specified based on the effects of considered factors on the water crisis. For example more precipitation in the area caused low water crisis and vise versa, due to the replacement of exploited water by new water resources. Therefore, each region with more precipitation can compensate the effects of water shortage. Based on similar concept all the considered factors was classified to 5 classes which are shown in Table 1.

After the organization of the data layers, second step was taken by weighting the layers in connection to their impact on water shortage and creation of water crisis in different geographic units of the Nishabur plain. In order to complete the process of weighting of layers in GIS, different methods were used with an emphasis on the

Table 1: The weighting of effective factors in water crisis rating in Nishabur plain

Factors	Class 1	Class 2	Class 3	Class 4	Class 5
Rainfall rate (mm)	310-350	280-310	240-280	200-240	160-200
Evaporation rate (mm)	2000-2300	2300-2600	2600-2900	2900-3000	3000-3200
Water table depth	10-50	50-80	80-100	100-120	120-140
Groundwater exploitation rate (mm^{-3})	400-600000	600000-1000000	1000000-1500000	150000-2000000	2000000-3200000
Groundwater falling rate	0-5	5-10	10-20	20-30	30-40
Permeability rate of lithological types	Alluvium and fans	Limestone	Alluvium terraces	Andesite, conglomerate, dolomite, colored mélange	Shale and marl
Land use types	1) Low dense rangeland and woodland 2) Bare lands	1) High dense rangeland and woodland 2) Dry farming	Urban areas	Irrigated farming	Orchards

ranking, rating and pair-wise methods (Jack, 1999). By considering the selected data layers and simplicity of the adopted methodology, ranking method was used in this research. In this method, all the considered data items were ordered based on their importance. It means that data were ranked from the most important to the less important. Then, the most popular weighting approaches including rank sum, rank reciprocal and the rank exponent were evaluated and the rank sum method were selected. Rank sum weights were calculated according to the equation that follows (Jack, 1999):

$$W_i = (n-r_j+1)/\Sigma(n-r_k+1) \quad (1)$$

Where, W_i is the normalized weight for the j^{th} criterion or factor, n is the number of the criteria under consideration (k = 1, 2... n) and r_j is the rank position of the criterion. Each criterion is weighted $(n-r_j+1)$ and then normalized by the sum of all weights, that is, $[\Sigma (n-r_k+1)]$. Table 2 shows the weights specified to evaluate data layered.

Then the calculated weights were used to prepare water crisis map in Nishabur Plain, the following formula was used for the overlaying of the layers and obtaining the water crisis sensitiveness:

$$WC = (P.w_1)+(E.w_2)+(WT.w_3)+(WO.w_4)+(LU.w_5)+(I.w_6) + (EX.w_7) \quad (2)$$

Which:

WC = Water Crisis,
P = Precipitation,
E = Evapotranspiration,
WT = Water Table,
WO = Water Overuse,
LU = Land Use,
I = Impermeability,
EX = Exploitation,
w_1-w_7 = The specified weights based on Table 2.

In order to prepare zonation map of water crisis for the study area, after determining the significance of each parameter and their weighting, GIS database was used to detect the areas experiencing water crisis.

Table 2: Weights specified to considered data layer based on rank sum method

Raw	Factors	Straight rank	Weight $(n-r_j+1)$	Normalized weight
1	Rainfall rate	1	7	0.250
2	Evaporation rate	5	3	0.107
3	Water table depth	3	5	0.178
4	Exploitation rate	4	4	0.142
5	Groundwater falling rate	2	6	0.214
6	Permeability rate	6	2	0.071
7	Land use types	7	1	0.035
	Sum	-	28	1.000

Using GIS overlay function, the water crisis map of the area was prepared. Accumulating the above layers was resulted in the final layer of raking the water crisis that classified to 3 main groups. The extraction of each primary data layer experiencing water crises is the other analysis that was conducted using GIS functions.

The determination of vulnerability of each land use classes to water crisis was carried out using crosstab analysis. In this step, water requirement for different agricultural products was calculated and finally management policies to decrease water crisis were presented.

ArcGIS (ESRI, 2004) package was used to access the required GIS analysis functions.

RESULTS

Zoning of areas based on water crisis: The study of each factor indicates the most vulnerable factors in relation to available water. In case of low amount of available water, there is not enough confidence to access the needed water. These conditions are the consequeses of aridity characteristics of the study area. Therefore, the recognition of regions with high susceptibility can be used for optimum management of restricted accessible water. Using GIS overlay function, the spatial distribution of the water crisis based on specified weighted factors was prepared that presented in Fig. 4. The map clearly indicates local variation of water crisis at various parts of the plain which shows that each part has crisis of different levels.

According to Table 3, about 23% of the plain has low crisis, 46% has medium and 31% has severe crisis.

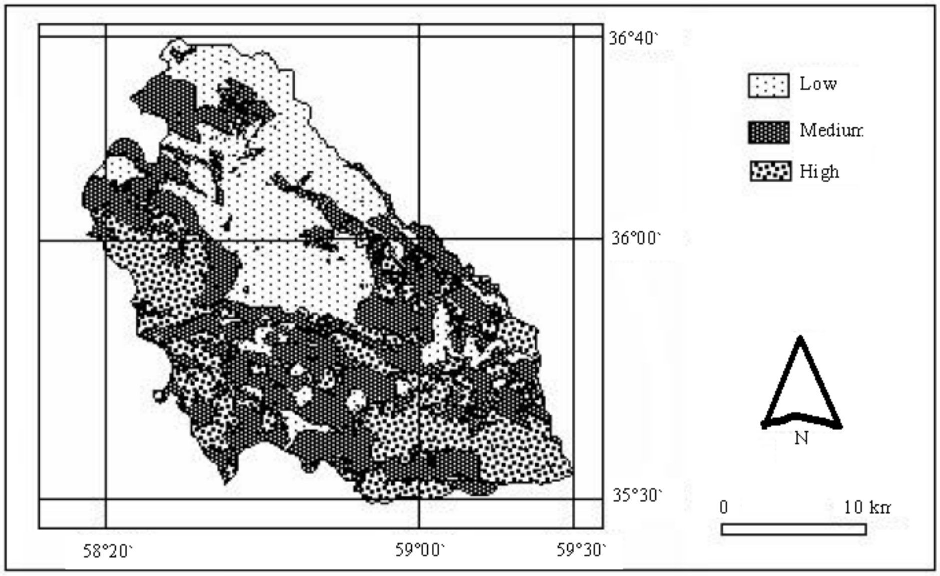

Fig. 4: Water crisis zonation map of Nishabur plain

Table 3: Extent of water crisis intensity in whole of area and in each land uses classes

Parameters		Crisis intensity Low	Medium	Severe
Total area	Area (km^{-2})	1723.0	3327.0	2250.0
	Area (%)	23.0	46.0	31.0
	Irrigated farming	22.0	47.0	31.0
	Dry farming	19.0	43.0	38.0
Crisis intensity in Land use types (%)	Orchard	7.0	31.0	62.0
	Urban area	100.0	0.0	0.0
	Rangeland	49.3	35.3	15.4
	Woodland	46.3	43.3	10.4
	Bare lands	10.0	78.0	3.0

The lowest crisis is observed in the eastern and especially northeastern parts of the plain. These areas have low permeability, high precipitation, while its water exploitation, falling and evapotranspiration are low. The combined effect of these factors has kept the water crisis at low level in these areas.

In the southern parts even though more water is exploited, however due to the presence of land uses consuming less water, water crisis is kept at medium level here.

Also the produced map indicates transition from northeast parts of the plain towards eastern and southern parts of the study area, higher evapotranspiration and lower precipitations rates are observable. Therefore in these areas water crisis with high intensive susceptibility is observable. The highest water consumption rate takes place at theses parts, though these areas enjoy a high permeability, but due to the land uses in which agricultural crops or fruit trees needing too much water are cultivated, water crisis is severe in these areas. The most severe water crisis is observed in the western and southern parts of the plain.

The review of the effects of considered factors on water crisis: The result of this study indicates that various complex factors play a role in the Nishabur Plain water crisis. The climate of the region especially its high temperature has led to high evaporation and consequently an increase in soil salt amount and also the untimely precipitation distribution and its scarcity are among the contributing factors as well. Droughts have had an indirect impact on this crisis especially the occurrence of this phenomenon in several subsequent years have led to more water exploitation from underground resources graving the crisis even more. In short, the temporal distribution of precipitation has varied in different years and the water table level has lessened at the end of the year compared to the early months of the same year. The water fluctuations of the last months of the year are harmonious with the precipitations, the highest of which occurs in the first half of the year.

The study of the annual relationship between precipitation rates and the water table indicates that the increase in precipitation has had no immediate impact on water tables. Therefore, it can be believed that the falling in the water tables can be largely attributed to over use.

One of the repercussions of over use is manifested in the decrease of water table's level so that it has been continuously lowered with an annual rate of 0.2 m since 1992 (Toos Ab Consultant Engineer Company, 1998).

Considering the fact that qanats and springs only drain the dynamic part of the aquifer, its over use is mainly occurred through wells. The number of wells has been rapidly increased since 1995 in a way that each year 43 new wells have been dug.

The calculation of the Nishabur Plain water balance indicates that considering the falling of water tables, the continuation of exploitation is leading to constant falling of water tables making the accessibility level even deeper.

Land use effects on water crisis: The land use is also considered a significant factor in the creation of water crisis. The largest area is devoted to aquaculture covering 43.1% of the plain. The main agricultural products of the area in terms of land coverage include wheat, barley, sugar beet, fruits, cotton, alfalfa, watermelon and so on (Table 4). In order to calculate irrigation water requirement of the Plain, the statistics of Khorasan Agriculture Organisation of 2001-2002 were used. Making use of individual crops' water requirements provided by Anonymous (2003) and based on cultivated area for each product, water needs was calculated. The data indicates that more than 126169 hectares of land has been cultivated that 88% of which (111999 ha) has been allocated to agricultural products while 12% (14170 ha) has been used for orchards. The whole irrigated farms with 94078 hectares constitutes 47.5% while the entire dry farming with 32091 hectares constitutes 25% of the farmlands. Dry farming crops have been cultivated in 26659 hectares while aquiculture has been practiced in 85340 hectares whereas dry and irrigated fruit gardens have covered 5432 and 8738 hectares, respectively (Anonymous, 2000). As indicated in the Table 4, the annual water need of the plain is about 500 million m^3.

Bearing in mind the scarcity of water resources at Nishabur Plain, water resources should be allocated to agricultural produces which have the highest benefit per cubic meter of water. The most intense cultivation is concentrated in the central and eastern parts of the plain on alluvial plains and foothills of deep soil which enjoy temperate climate and annual precipitation of more than 150 mm. One of the major constraints of this part is the falling of water tables due to extensive use of groundwater.

Table 3 presents the water crisis intensity for different land use classes. The 30% of aquiculture land use covering 40% of the plain is affected by severe water crisis, which by considering the crops water needs, its farming patterns needs to be improved. The same fact is true for fruit orchards, with 62% of which situated in the severe water crisis area. About 15% of the rangelands is also situated in severe water crisis area, which can have direct effect on cattle's grazing and consequently on meat and diary productions. Therefore, necessary precautions should be taken in this area. About 10% of woodlands also suffer from severe water crisis, but since this land use is not directly involved in agricultural products, it is important from the point of environment concerns and in the relevant woodland development plans, so, emphasis should be put on the planting of types resistant to drought.

For evaluation of the adopted model, field studies were taken place. Field observations confirm that non-suitable crop types consume all the water fetched by the wells. So these conditions have increased intensity of water crisis in these regions.

Table 4: The estimated water needs in Nishabur plain based on cultivated products

Product types	Cultivated area (ha)	Water needs (m^3 in hectares)	Water need in year (m^3)
Wheat	36700	4910	180197000
Barely	19300	3710	71603000
Beetroot	10499	8690	90801810
Orchards products	8737	7500	65535000
Cotton	4910	9130	44828300
Alfalfa	4100	8600	35260000
Melon	3164	7020	22211280
Corn	1890	6720	12700800
Tomato	940	7150	6721000
Oblong	640	6990	4473600
Squash	459	4060	1863540
Vegetables	365	7810	2850650
Bean	265	6840	1812600
Pea	210	6270	1316700
Cucumber	192	6050	1161600
Potato	180	7810	1405800
Sum	92502	-	544742680

DISCUSSION

Water crisis in contrast with other natural disasters or environmental hazards is more affected by human activity. In other words, in addition to effects of environmental conditions of areas such as precipitation and permeability rate in existing water crisis, the quality of land uses for different proposes has an important role in the creation of crises caused by the shortage of water especially for areas with agricultural use.

One of the most important factors in the management of available water is the collection of correct and current data. GIS offers the ability to manage spatial and non-spatial data usable for such purposes. The finding of this research in delineation of the areas facing water crisis and monitoring of these areas for formulating proper policies can help governmental bodies in the controlling of the existing water crisis. Results of this study show the role of GIS in the management of various data in order to show regions facing water crisis. The use of different functions of GIS to present proper policies for agricultural activities and to introduce the optimum species fitting with environmental conditions and the shortage of water is also demonstrated. Also it is debated that the recognition of most important environmental factors affecting the water crisis is the potential deployment of GIS in such studies. This knowledge helps to manage and control the impacts of affected environmental layers. Generally, if collected data includes comprehensive and accurate data, the results will be more valuable and reliable.

There is no bright perspective for the future use of these water resources and the present conditions necessitate creating a balance between the cultivation type and water availability in the plain. Based on the water crisis zonation map of Nishabur Plain, it is somewhat evident that land use has the greatest effect on the water crisis of Nishabur Plain.

The results of this study indicate that for the proper management of water crisis in these areas, it is necessary to concentrate on activities such as land use management to decrease intensity of water crisis. Because the study of the aquifer shows that the underground water resources of the plain are not large enough to supply this huge volume and therefore the water crisis of the plain is expected to get worse in the coming years.

Factors such as precipitation, evapotranspiration, permeability and water table depth are effective factors in the optimal usage of land of each agricultural plain. These factors can not be controlled or changed. Therefore, the water exploitation rate from water resources and especially the land use should be given due attention and adjusted to the special conditions of each area. For instance, dry farming is the most suitable method for cultivation and crops needing too much water should be avoided. The water exploitation needs to be decreased significantly and only those crops having lower water consumption should be cultivated.

In order to increase the productivity of agricultural sector, first of all critical and the most effective factors have to be identified (Mehrzad and Homan, 1983) and due to the shortage of water resources, the planning and research should focus on the promotion of water efficiency.

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