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Original Research

Mapping Multi-Year Groundwater Depth Patterns from Time-Series Analyses of Seasonally Lowest Depth-to-Groundwater Maps in Irrigation Areas

S.T. Akkaya Aslan[1]*, K. S. Gundogdu[2]

[1]Department of Agricultural Structures and Irrigation, Faculty of Agriculture, Uludag University, Bursa 16059, Turkey
[2]Department of Agricultural Structures and Irrigation, Faculty of Agriculture, Uludag University, Bursa 16059, Turkey

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Abstract

In large irrigation projects, observing and evaluating groundwater depth (GWD) for crop production is crucial. To accomplish these goals, GWDs are measured over certain time intervals, especially during irrigation season, when depth and level maps are prepared and analyses on the target are made. These maps are used for a multi-year observation of GWD. In this study, we present an alternative method that can be used for multi-year lowest GWD evaluations. The method evaluated the spatial and temporal relationships among the classes of GWD in the study area, in their typical locations (areas where the GWD classes are most frequently located), and the alternative GWD classes in those locations in any of the years of the analyzed time-series. As a case study, the method was applied to data of the multi-year (1990–2000) GWD observations in the Mustafakemalpasa (MKP) irrigation project (19.370 ha), which is located in the Marmara Region (northwest Turkey). The most widespread typical GWD class for the analyzed time period was identified as GWD-III (between 101–200 cm), which covered 98.18% of the total area.

Keywords: groundwater depth, time-series analysis, irrigation, GIS

Introduction

Lowland areas of shallow water tables are important for human and wildlife habitats and play a crucial role in the global energy cycle. In Europe, many of these areas are drained and used for agriculture [1, 2]. In such areas, the groundwater table and its temporal variability can be of great economic and environmental importance [3, 4]. High groundwater levels can cause crops to perish and agricultural fields to become inaccessible for machinery and harvesting, whereas moisture availability and growth is reduced when the capillary fringe drops below the root zone in agricultural areas [5, 6].

Groundwater rising to the crop root zone is one of the most unfavourable effects of irrigation projects. Because this rise occurs slowly in some cases, this problem tends to emerge over years [7]. Therefore, water managers want to be informed about the variation of water-table depth in both space and time [8]. For this reason, groundwater levels are regularly observed in the irrigated areas. Observing and evaluating the groundwater depth in irrigation areas is quite important in order to see changes in the groundwater due to irrigation, to determine the problematic areas or areas that are likely to be so, to make the

*Corresponding author; e-mail: akkaya@uludag.edu.tr

irrigation planning, and to take the necessary precautions. Throughout the irrigation season, changes that take place in the groundwater are evaluated with the critic values at which groundwater depth is the lowest (groundwater is the nearest to the soil surface) [9]. Seasonal groundwater lowest depth maps are obtained by taking the lowest groundwater values measured from each well during the irrigation season. With the help of these maps, areas that form risk in groundwater are determined for each year and evaluated [9-12].

Many various methods are used in evaluating the groundwater data. More recently, methods have been sought to identify the properties that determine the dynamics of a groundwater system. Such methods regard the problem from the viewpoint of system identification or time series analysis [13-15], or use the somewhat less sophisticated multiple regression methods. Time series method is commonly used in to evaluate the data that are measured over certain time intervals such as groundwater measurements. Time series modelling refers to a statistical approach to analyze and describe one or more time series. Time series modelling has been applied in groundwater studies since the 1980s. However, the framework applied for modelling groundwater time series involves several practical problems influencing the results of these models; some problems even limit the applicability of these models to the field of groundwater hydrology altogether [16]. Some recent applications of the time series theory to hydrology include, but are not restricted to, drought hazard assessment [17], analysis of groundwater table fluctuations [1], filling in data gaps [18-20], and spatial interpolation of groundwater heads [12], forecasting groundwater levels [21]. In studies performed to assess groundwater parameters, time-series analyses are carried out by using either individual groundwater observation well values or values of groundwater observation wells grouped according to some criteria. These methods may be insufficient for monitoring groundwater parameters both temporally and spatially. Furthermore, GIS has an important role in the studies that have been carried out related groundwater recently [22-24, 10, 11]. With the development of GIS technology, three dimensional modelling of the spatial data [16], observing and analysing both temporal and spatial data, and displaying the results are becoming easier [25].

In this study, we present an alternative method that can be used for multi-year groundwater depth (GWD) evaluations by combining time series' feature of analysing multi year data and GIS's feature of analysing spatial data. The method investigates the spatial and temporal relationships between GWD classes in the study area, in their typical locations (areas where the GWD classes are most frequently located), and the alternative GWD classes in those locations in any of the years of analyzed time-series. As in a case study, the method was applied to data from multi-year (1990–2000) GWD observations in the Mustafakemalpasa (MKP) irrigation project (19,370 ha), which is located in the Marmara Region (in northwest of Turkey).

Experimental Procedures

Study Area

The MKP irrigation project is the largest irrigation project in the Marmara region (northwest Turkey) and covers an area of 19,370 ha [26]. The MKP irrigation project is located between 28°22′ E, 40°12′ N and 28°31′ E, 40°02′ N (Fig. 1).

There are 200 observation wells in this system, which are used to make monthly observations about water-table depth (distance between the soil surface and water-table (cm) and groundwater salinity (dS/m at 25°C) [9]. Observation wells are built in such a way that depth to groundwater measurements can be made as deep as 4 meters. Irrigation water is diverted to the irrigation area by means of a regulator and there are two main canals, one on the right and the other on the left bank. Drainage canals are parallel to the irrigation system and drainage water is removed from the project area through 5 pumping stations.

The climate is semi-arid, with a mean annual temperature of 14.2°C and mean annual precipitation of 693 mm. Project soils are of young alluvial character. 54.9% of the soil is clayey-loamy and clayey, 34.3% is loamy sand-loam and 10.8% is sandy clay, sand [27].

Seasonally Lowest Depth to Groundwater Maps

In the case area, the irrigation season starts in April and continues until October. One of the restrictive factors for crop production during the irrigation season is shallow groundwater. For this reason, by use of the monthly groundwater values that are measured during the irrigation season (from April though October) in the Mustafa Kemal Pasa project area and considering the lowest levels of the groundwater in each well, the seasonally lowest depth to groundwater map for each year was created. In this study, seasonal lowest groundwater values were used in the multi-year mapping of GWD. For this aim, monthly GWD maps first were derived from observed GWD values from April to October for every month between 1990–2000 by an iterative finite-difference interpolation technique [28, 29]. An ArcInfo grid module, which consisted of 50-x-50–m grid cells, was used in preparing these maps [30]. Later, to obtain seasonal lowest GWD maps, the *ArcInfo Grid MIN()* process was applied and eventually, seasonal lowest groundwater depth (LGWD) maps, one for each irrigation season, were produced. The *MIN()* function uses multiple-input grids to determine the minimum value on a cell-by-cell basis [30]. Here, we refer to lowest groundwater depth as *groundwater depth* only.

Time-Series Analysis of Groundwater Depth Maps

Martínez-Casasnovas et al. [31] presented a method for preparing a multi-year crop pattern map from time-series and satellite images. In our study, the method mentioned

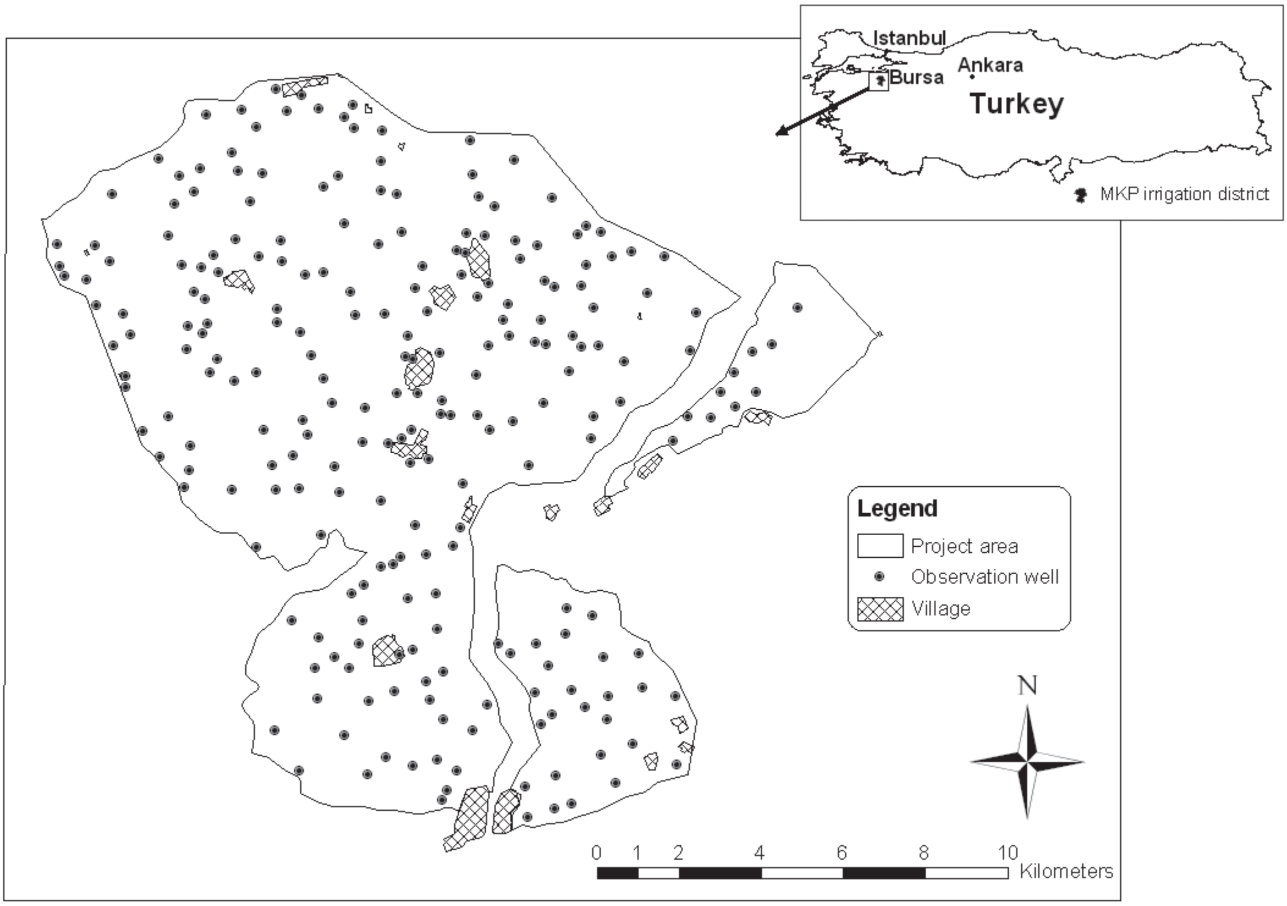

Fig. 1. Mustafakemalpasa irrigation project.

above was adapted to the preparation of a multi-year GWD map. The method investigates the spatial and temporal relationships between the main classes in the study area, in their typical locations (areas where the GWD classes are most frequently located), and the alternate classes in those locations in any of the years of the analyzed time-series. Groundwater depths in LGWD maps were grouped in five classes, as given in [32]. The 0–50 cm interval of groundwater depth was expressed as GWD-I; the 51–100 cm was expressed as GWD-II; 101–200 cm as GWD-III; 201–300 cm as GWD-IV; and 300 cm or greater as GWD-V.

The method for mapping the typical locations of the main GWD classes present in the study area was based on a frequency analysis applied to the time-series of LGWD maps: the number of times that a GWD class is present at a specific location (raster pixel). To achieve this, first LGWD class maps had to be reclassified to produce annual per-GWD class maps (e.g., GWD-I-1990, GWD-I-1991, GWD-II-1990, etc.). Next, for each depth class the seasonal per-depth class maps were added together by a sum operation. These sums resulted in different frequency maps, one for each depth class, which could be reclassified according to the user criteria. In this case, we used 50% as the threshold, as did [31]. Therefore, the typical location of a GWD class was composed of the pixels in which the GWD class is repeated in >50% of the analyzed years (6 years in the present case study).

Mapping Multi-Year Groundwater Depth Maps

Once the typical-location areas of the GWD classes were mapped, it was necessary to know which other GWD classes were present at these locations in any of the years in which a typical GWD class was not present. To achieve this, *ArcInfo Grid* combine operations were applied to map all existing combinations between the typical-location GWD class maps and the frequency-distribution maps of each GWD class. The *combine()* function combines grids on a cell-by-cell basis so that a unique value is assigned to each unique combination of input values [30]. Each of the resulting maps indicates, over the typical location of a given GWD class, the years in which one particular alternate GWD class has been present.

Because more than one other alternative GWD class can be present at the most frequent locations of main GWD classes during the considered time-series, the resulting maps had to be combined for each main GWD class to obtain the complete GWD class pattern in each pixel of the study area. This combination was achieved by applying a special codification to the combining maps, which allows the association of GWD classes at a specific location to be tracked. The codification consisted in reclassifying the different combining maps for each main GWD class to a power of two, starting with the value 1 [31]. These codes were labelled as 1, 2, 4, 8, 16, etc. This encoding method has also been used for other very different purposes, such as the determination of the flow direction to extract topographic features from digital elevation data by means of GIS analysis [33]. In the current work, if GWD-I was the main GWD class, for example, alternate GWD classes could be reclassified with the following codes: GWD-II (1), GWD-III (2), GWD-IV (4), GWD-V (8), and so on. After the *Grid combine()* operation, some codes might be available repeatedly on each unique combination. To run the unique codification system, it was stipulated that each code would be used one time in each unique combination. This stipulation was met through a program that we wrote in ArcMacro language. Once it had been executed, for each main GWD class the unique value sum of the reclassified combining maps resulted in a map that allowed the identification of multi-year GWD class patterns.

Finally, the different LGWD class patterns maps (one for each main GWD class) were merged using a *merge()* operation in ArcInfo Grid.

Results

In the study, main GWD classes and typical distribution areas were determined using the GWD values that were observed annually (1990-2000) in the MKP irrigation project area and a multi-year GWD classes pattern map was also obtained. Obtained results of the study are presented below.

Main GWD Classes and Typical Distribution Areas

Table 1 summarizes the area covered by each depth class in LGWD maps. Main GWD classes and typical distribution areas are given in Table 2. Table 1 depicts a great variability of GWD class surfaces in the years before 1996. After 1997, variability of GWD class surfaces decreased. This decrease may have been a consequence of the turnover of the operation from the state to the Water User Association (WUA) after 1996. As seen in Table 1, over 11 years' time, the GWD-I class covered the least area, and GWD-III covered the most area. The same situation can also be seen in annual results, except for the 1994 values. During the study period, the area with the GWD-III class ranged from 4657 to 19.370 ha. The GWD-IV class covered roughly the second largest area.

Only one typical GWD class, GWD-III, was identified in the case area, and it covered 98.18% of the total area. In the rest of the area a typical GWD class falling within the stated constraints was not identified; thus, the remaining areas are given as "Other" in Table 2.

Multi-Year GWD Classes Pattern Map

The results of the method for mapping multi-year GWD class patterns in the period 1990–2000 yielded a map with 12 classes. Fig. 2 shows the alternative classes that emerged over the 11-year-period in the GWD-III class, the largest main class (Table 2) covering 98.18% of the project area; the spatial values of the map are given in Table 3.

The MKP project area is densely irrigated between April and October. Also, most of its soil consists of clay and clayey sand, and the drainage system is operated with a discharge system pump. For this reason, groundwater depth can change depending on the irrigation water given to the system, drained water, and crop evapotranspiration values.

As seen in Table 3, the area with a main GWD class of GWD-III but an alternative depth class of GWD-IV covers 74.43% of the total area; the area with an alternative depth class of GWD-II covers 8.57% of the total area. During all years in the study time period, the area where only the GWD-III class was seen was 10.21% of total area. Consequently, during the considered time period groundwater depth in the case area did not fluctuate much. In their study, Korukcu et al. [10] formed groundwater depth surface maps in the raster format from the annual measurements in order to determine the spatial change of groundwater depth for the two consecutive years. In the next stage, they got subtraction made on the pixel values of the raster maps of these two years. Consequently, they determined the areas where groundwater depth did not change, or decreased, or increased on the obtained new raster map. As seen from the results they obtained, in the study, the spatial change in groundwater in comparison to the year before was interrogated setting out from the distinction between the two consecutive years, yet a multi year analysis was not performed. Diker et al. [11] used the groundwater level values for July of the 3 years before and after the turnover in order to determine the effect of the practice of turning over the irrigation management to Water Users' Association on groundwater level. They created monthly raster groundwater surface maps using the Inverse Distance Weighted Interpolation method. In order to facilitate the comparison of the maps belonging to the periods before and after the turnover, they computed the pixel level mean of the raster maps of the 3 years before and 3 after the turnover separately. Thus, they used the two obtained raster maps to compare the periods before and after the turnover. Despite using multi year data, Diker et al.[11], did not take the temporal change in these data but the lowest or highest groundwater values within the years discussed. Thus, they carried out only spatial analyses with the long year data. In their study in 2003, Sainato et al. [22] used geostatistical kriging interpolation technique to obtain water table level, depth, and groundwater salinity maps. Sainato et al. [22] determined the spatial changes only within the year by using groundwater values (such as groundwater level, depth and salinity) with the techniques given above. In recent years, spatio-temporal data models have shown great development and it was commonly in various sectors. Among these data models, Snapshot, Event

Table 1. Surface (hectares) of seasonally lowest groundwater depth (GWD) in the Mustafakemalpasa irrigation project, 1990–2000.

Year (in irrigation season)	Areas of seasonal groundwater, lowest depth classes (ha.)				
	GWD-I	GWD-II	GWD-III	GWD-IV	GWD-V
1990	105	1265	14617	3380	4
1991	26	1608	17222	515	0
1992	0	630	10123	8588	29
1993	0	28	12980	6190	173
1994	0	4	4657	14299	410
1995	0	522	17976	873	0
1996	4	72	19206	88	0
1997	0	0	19370	0	0
1998	0	3	19368	0	0
1999	0	0	19370	0	0
2000	0	0	19370	0	0
Annual mean	**12**	**376**	**15842**	**3085**	**56**
S.D.	**32**	**575**	**4848**	**4736**	**128**

Note: GWD-I: 0 -50 cm. GWD-II: 51-100 cm. GWD-III:101-200 cm. GWD-IV: 201-300 cm GWD-V: 300 cm >

Table 2. Area of the most prevalent lowest groundwater depth (GWD) classes in their distribution zones in the Mustafakemalpasa irrigation project, 1990–2000.

Water-table GWD	Typical distribution zones (ha)	% with respect total area
GWD-III (101-200 cm)	19017.5	98.18
Other (low frequency pixels)	352.5	1.82
TOTAL	**19370**	**100**

Table 3. Area of multi-year groundwater depth GWD classes in the Mustafakemalpasa irrigation project, 1990–2000.

GWD classes	Area (ha)	% with respect total area
(GWD-III)	1976.75	10.21
(GWD-III) + (GWD-IV)	14417.75	74.43
(GWD-III) + (GWD-IV) – (GWD-V)	120.25	0.62
(GWD-III) + (GWD-II)	1660.5	8.57
(GWD-III) + (GWD-II) – (GWD-IV)	596	3.08
(GWD-III) + (GWD-II) – (GWD-V)	47	0.24
(GWD-III) + (GWD-II) – (GWD-IV) – (GWD-V)	85.75	0.44
(GWD-III) + (GWD-I)	10	0.05
(GWD-III) + (GWD-I) – (GWD-IV)	13	0.07
(GWD-III) + (GWD-I) – (GWD-II)	81.75	0.42
(GWD-III) + (GWD-I) – (GWD-II)- (GWD-IV)	8.75	0.05
Other (low-frequency pixels)	352.5	1.82

Note: GWD-I: 0 -50 cm. GWD-II: 51-100 cm. GWD-III:101-200 cm. GWD-IV: 201-300 cm GWD-V: 300 cm >

Oriented, O-O and Moving Objects models can be used in the raster-featured data structure [25]. Both spatial and temporal analysis and evaluation of many data are becoming easier with the development of GIS and thus Spatio- temporal data models.

To this end, in the study, we used the multi-year crop pattern map method of Martínez-Casasnovas et al. [31], which was development to obtain multi-year crop pattern maps from satellite images. In order to use the developed method for multi-year groundwater depth patterns mapping, seasonally lowest depth-to-groundwater maps were created in raster format. In their study, Martínez-Casasnovas et al. [31] used the raster format plant pattern maps that were produced by classifying satellite images. This method can be successfully used in forecasting the problematic areas and the areas that are likely to create problems in the future in terms of groundwater depth. Similarly, the method is of a character that enables it to be used in data clusters for multi-year raster maps.

Conclusions

In this study, both temporal and spatial analysis of the groundwater depth change over the irrigation seasons of 11 years in MKP irrigation project was made. While carrying out this analysis, the method developed by [31] in order to obtain a multi-year plant pattern map from satellite images was used and successful results were obtained. With the handled method, data groups that were most frequently repeated in the long-term study area were determined and a multi-year GWD class pattern map was obtained through main GWD classes of the study area and typical distribution area maps. According to the results, the class with the highest frequency of the lowest groundwater level for 11 years is GWD-III, which covers 98.18% of the total area. Furthermore, other alternative class values were obtained as well as the main class that was most frequently seen for long term. For example, the area with a main GWD class of GWD-III, but an alternative depth class of GWD-IV covers 74.43% of the total area.

These obtained results show that the usability of the method in the effective evaluation of both temporal and spatial changes of the groundwater depth data. This method can be used for multi-year analysis of groundwater depth data. In the same way it can be used in the evaluation of such issues as salinity, nitrate concentration and water quality. Furthermore, since the method uses the GIS facilities effectively, it can help analyse the effects of several parameters such as climate, soil, irrigation method and irrigation amount on the temporal and spatial change in groundwater. Thus, the method can be used more effectively in observing and evaluating the groundwater in irrigation areas, keeping the water table on the optimum level and determining problematic areas and the areas that might create problems. In future studies, the use of facilities of spatio-temporal data method in multi-year evaluation of groundwater depth can be searched.

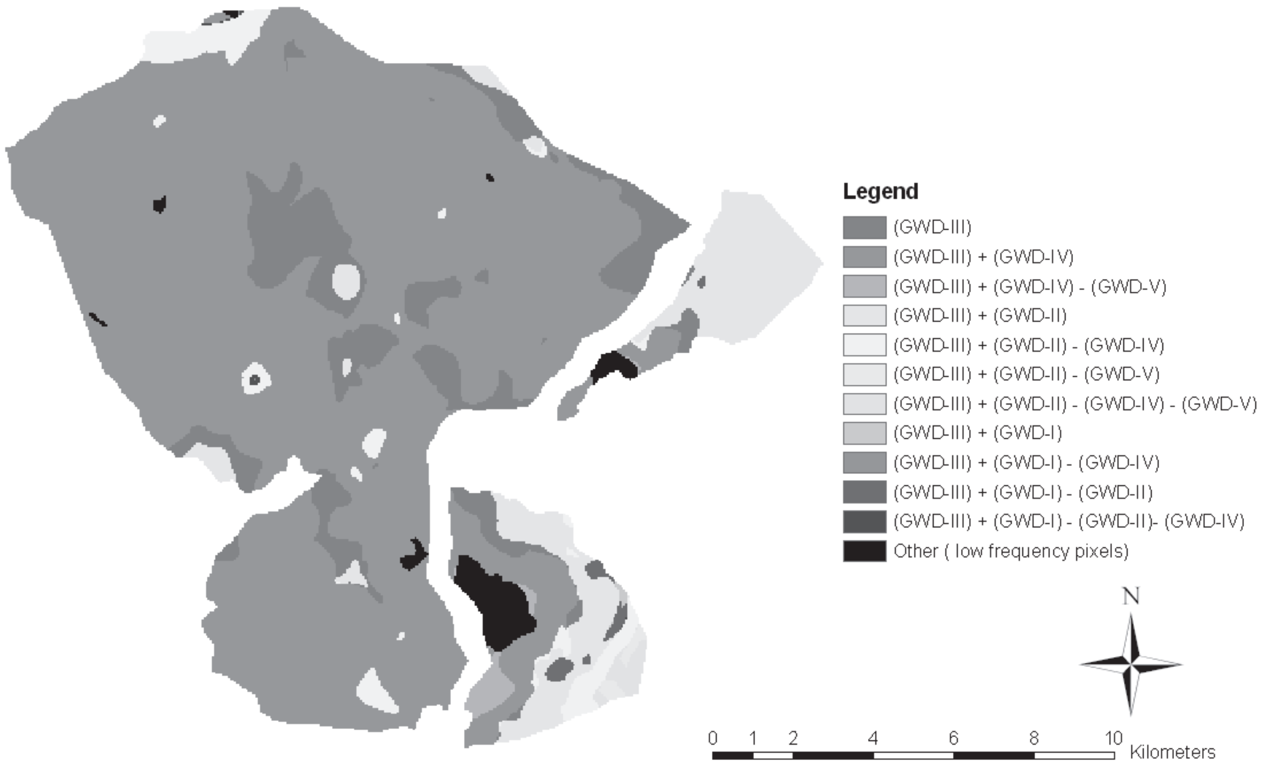

Fig. 2. Multi-year lowest groundwater depth (GWD) patterns in the Mustafakemalpasa irrigation project, 1990–2000.

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