Hydrodynamic zoning of complex aquifer systems: the Zagreb aquifer (Croatia)

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Abstract: Hydrodynamic homogenous zones within the Zagreb aquifer system were determined by statistical multivariate analysis - the principal component analysis. Significance of individual aquifer recharging sources was determined from correlations of the Sava River level time series and rainfall rates, along with the change in the groundwater tables.

Key words: multivariate statistics, hydrodynamic homogeneous zones, Zagreb aquifer system

Introduction

The Zagreb aquifer system is located in the NW part of the Republic of Croatia (Figure 1). The aquifer system is of Quaternary age[1]. Considering hydrogeological aspects, the deposits are divided into three basic units: aquifer system overburden; shallow Holocene aquifer; and deeper aquifers from Middle and Upper Pleistocene. The Sava River divides the Zagreb aquifer system into two parts. The river is in direct hydraulic connection with the shallow aquifer. The Zagreb aquifer system accommodates important well fields as the part of the system supplying the City of Zagreb and its greater area with water. The groundwater table monitoring has been conducted continuously since 1990 in more than 220 observation well (piezometer) locations, mostly in the vicinity of the Zagreb well fields. Monitoring is carried out in shallow and deeper aquifers, and the measurement data are mostly used for preparation of water-table contour line maps for a particular moment in time. Aim of this paper is to determine homogenous zones within the Zagreb aquifer system with identical groundwater table changes in time. Homogenous zones point to aquifer recharging conditions prevalent in particular parts of the complex aquifer system and significance of geological and hydrogeological characteristics in fluctuating patterns of the groundwater table change, and enable making conclusions on prevalent groundwater flow conditions in particular parts of the system. The paper applies multivariate statistical analysis - *principal component analysis* (*PCA*), which allows for incorporation of all existing groundwater table measurement results for the individual observation well locations. In this paper, a data analysis procedure is used as explained by Winter et al.[2]. Transformation of correlation matrix and variance-covariance matrix into the principal component loading matrix and principal component scores matrix enables determination of differences in groundwater table changes in particular parts of the system and determination of representative hydrographs that describe fundamental characteristics of the fluctuation pattern in locations that accommodate individual observation well groups. The data analysis includes measurement results for 75 observation well locations and data series for the period 1990-2000, i.e. total of 1025 measurements per location. The original data matrix, NxM matrix, includes N table measurements (N rows) for each of M observation well locations (M column). The data are standardized (*mean value* 0, *standard deviation* 1) so that the values (groundwater tables) for

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individual variables (observation well locations) are given equal weight. Additionally, an impact of the main factors affecting the shallow aquifer recharging is assessed. The *cross-spectrum (Fourier) analysis* is used in order to determine existence of significant correlations between the Sava River, rainfall, and groundwater table change time series. The observation well locations selected as representative and used in the analysis are the locations for which daily groundwater table measurements are available.

Figure 1. Location of the Zagreb aquifer system, Croatia

RESULTS AND DISCUSSION

The principal component analysis results show that the observation wells are grouped in eight groups (Figure 2). Each group is determined from the component loading graph for the first and second principal component, that explain most of the total data variance, while each group has the same fluctuation pattern for the groundwater table. By comparison of characteristic hydrograph shapes for each group of observation wells with hydrograph component scores for individual principal components, the groups were singled out for which

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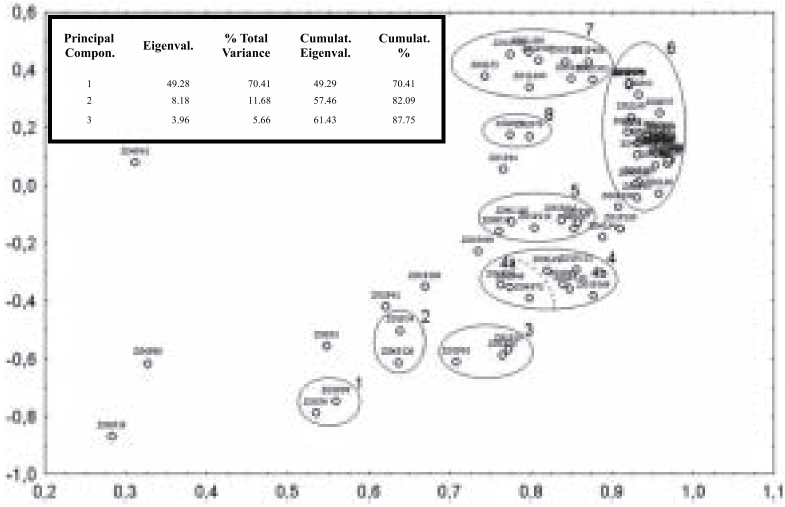

Principal Compon.	Eigenval.	% Total Variance	Cumulat. Eigenval.	Cumulat. %
1	49.28	70.41	49.29	70.41
2	8.18	11.68	57.46	82.09
3	3.96	5.66	61.43	87.75

Figure 2. Plot of component loadings for principal component 1 versus principal component 2

the groundwater table fluctuation pattern could be described with representative hydrograph component scores. Hydrographs for the locations of the observation wells from the groups 5 and 6 are identical to the hydrograph component scores for the first principal component (Figure 3). These observation wells are installed in the zone of operating well fields and discharge area of the aquifer system. The fluctuation pattern is equal for the shallow and deeper layers, and it reflects the impacts of the regional groundwater flow from west towards east, intensified impact of the vertical component of groundwater flow in this part of the system, and the Sava River impact. The hydrographs for locations of the observation wells from the groups 1, 2 and 3 are identical to the hydrograph component scores for the second principal component (Figure 3). These observation wells are located at the edge of the aquifer system, where the Sava River impact is less intensive or the water wave propagation is significantly lagging in time. Additionally, the impact of pumping at the existing Zagreb well fields is either negligible or nonexistent.

Contrary to the observation wells from the groups 1 and 3, which are located on the left Sava bank which has local recharging conditions that influence change in the groundwater levels in the shallow layer, the observation wells from the group 2 are located on the right

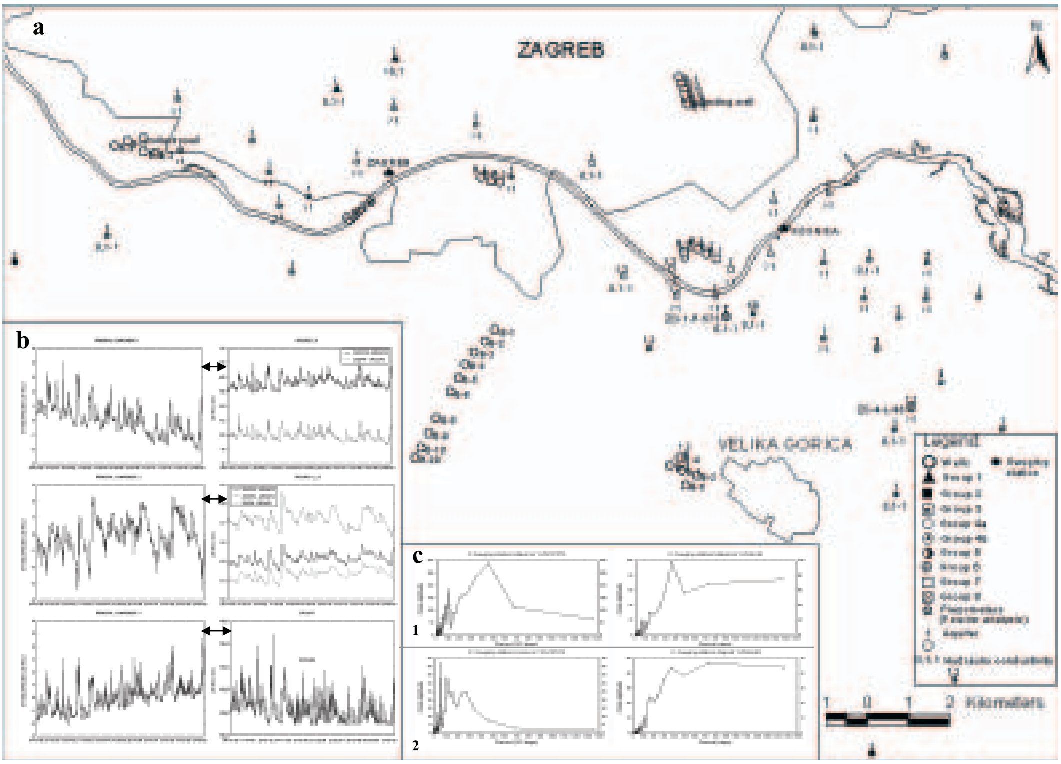

Figure 3. a) Distribution of groups with different groundwater level fluctuation pattern; b) Water level fluctuation pattern in observation wells: hydrographs for the most significant groups of observation wells compared with hydrographs of principal components factor scores; c) The plots of significant correlations between the time series of: (1) rainfall (mm/day) – groundwater tables (m a.s.l.), (2) the Sava R. levels (m a.s.l.) – groundwater tables (m a.s.l.)

Sava bank and they indicate existence of lasting seasonal conditions under which the deeper aquifers are recharged. Also, the existing differences between the said groups are also a consequence of different aquifer permeabilities. The hydrographs for the locations of the observation wells from the group 7 are identical to the hydrograph of the component scores for the third principal component (Figure 3). These observation wells are located immediately by the Sava River, and intensive fluctuations in the groundwater tables reflect fast and intensive impacts of changes in the river water levels on the groundwater tables within the belt by the river. *The cross-spectrum (Fourier) analysis* confirmed that significant correlations exist between the groundwater table changes and rainfalls and the Sava River water levels. There are certain regularities in distribution of maximum correlations, which depend on the distance of the observation wells from the Sava River. In locations of observation wells which are the most distant from the Sava River, maximum correlations between the groundwater table time series and the rainfall and the Sava River time series have been determined for a period of more than or equal of one year. Locations of observation wells, which are the closest to the Sava River, show higher dependence on the river influence, which is reflected in decreasing period of maximum correlation between the time series of the groundwater tables and the Sava River. Influence of rainfall in the vicinity of the Sava is masked by the river impacts, regardless of the overburden thickness.

Conclusion

The principal component analysis determined homogenous zones in the Zagreb aquifer system with identical fluctuation pattern of the groundwater tables. Two homogenous zones were formed on the left Sava bank that run in parallel with the Sava River. Although the groundwater table changes are attributed to the unique hydrograph component scores of the second principal component, the local conditions for recharging of the shallower aquifer and gradual decrease of the hydraulic conductivity coefficient going from the Sava River towards the river valley cause differences in the fluctuation patterns of different zones. The zones in the right Sava bank have very different fluctuation patterns of the groundwater tables. The lasting seasonal conditions of the aquifer recharging, significantly disturbed in the zone of the operating well fields, are prevalent in the western and central part of the system. The Sava River impact in the eastern part of the system intensifies, same as the vertical component of the groundwater flow in the aquifer system discharge area. The c*ross-spectrum (Fourier) analysis* confirmed the importance of the Sava River for the aquifer recharging, particularly in the eastern part of the system. The river impact is considerably higher in the locations closer to the river. The rainfall influence, which is significant for the locations distanced from the river, is masked in the vicinity of the river by considerably more intensive impact of the river, regardless of the overburden thickness.

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