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Detection and evaluation of changes induced by the diversion of River Danube in the territorial appearance of latent effects governing shallow-groundwater fluctuations

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SUMMARY

The paper assesses the impact on the fluctuation of the shallow-groundwater table of the diversion of the Danube upstream from the Gabčikovo/Bős hydroelectric power plant in a hydraulically connected, geologically identical, and structurally not decomposable geological area in North-West Hungary. On the basis of shallow-groundwater level monitoring data the impact was traced back to the effect of the Danube's changed flow course, and quantized for the whole study area.

To this end the influence of the river had to be separated from the effect of precipitation. The means chosen was the application of dynamic factor analysis to the registered hydrograph time series. We conclude that the originally homogeneous and dominant effect of the Danube has split and now consists of a diverted and a returning component (downstream from the power plant), and that this is a likely cause of ram-effect and river bed clogging. Furthermore the effect of precipitation ceased to be suppressed, and came to the fore.

1. Introduction

The second largest plain in the Carpathian Basin is the Kisalföld (Small Hungarian Plain). It is divided into two parts by the Danube. Here, the main channel of the Danube forms the natural border between Slovakia and Hungary. The Szigetköz floodplain is part of the Kisalföld, it is on the right bank of the Danube, on the Hungarian side. It is a huge island; to the north the main branch of the Danube borders it for 57.6 km, while on the south the Mosoni branch (in Hungarian, Mosoni-Duna) is the border for 121.5 km. Its area is 375 km^2, and its elevation is 115–125 m above sea level in the northwest (so-called Upper-Szigetköz/Felső-Szigetköz) and 110–115 m in the southeast (so-called Lower-Szigetköz/Alsó-Szigetköz).

The sediment carried by the Danube continuously fills the sinking basin of the Kisalföld. The Pliocene (Pannonian) sandy-clayey sediment sequence is more than 2000 m thick at the deepest point, while the Quaternary sandy gravel deposit series is 100–250 m thick.

Until October 1992, the level of the shallow-groundwater was uniform; it was controlled by the natural water level fluctuation of the Danube. The several hundred-meter thick hydrogeologically homogeneous aquifer also had an influence on it. In October 1992, the Slovakian hydroelectric power station at Čunovo (Dunacsúny[1]) began operation at the 1851 + 750 river km, and since then the natural fluctuation of the Danube has changed, with the majority of the Danube's flow being diverted to the insulated power-plant canal that rejoins the original riverbed only at Palkovičovo (Szap), at the 1811

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[1] As Slovakian and Hungarian have different names for the same place, hereinafter where the text mentions a place in Slovakia, the Slovakian name will be given, followed by the Hungarian name.

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river km. Therefore, the original 2000 $m^3 s^{-1}$ mean discharge in the natural river network fell drastically. The Mosoni branch retained 10–20 $m^3 s^{-1}$ flow, while the original Danube bed retained only 250–350. Consequently, water level in the riverbeds dropped several meters, and by 1993 some of the Danube's branch rivers had dried up. As the subsurface aquifer of the area is in close connection with the surface water network, the level of shallow-groundwater dropped significantly as well (Bárdossy and Molnár, 2003a). To amend this dangerous situation, 15 $m^3 s^{-1}$ extra water was pumped from the reservoir to the branch system between July 20 and October 15 1994. To achieve a more lasting improvement, since 1995 Slovakia has increased the annual mean water flow to the original Danube bed to 400 $m^3 s^{-1}$. Furthermore, in 1995 Hungary built a submerged weir at Dunakiliti with a 123 m a.s.l. spillover, so the water level increased in the original bed for 10 km behind the weir, and the surface water network received more water as well. The water supply to the Mosoni branch has been increased, resulting in a growth in discharge to 40 $m^3 s^{-1}$ (Fig. 1).

The effect of the Danube on the water table was first detected by Honti (1955), Ubell (1959), and Rónai (1960) in the very early stages of the operation of the shallow-groundwater monitoring well system, set up in the early fifties in the Kisalföld. The estimated width of the area affected by the river differs substantially in the literature of the time, some (e.g. Honti (1955) and Rónai (1960)) put it at 2–4 km, while others (Ubell, 1964) estimate it at 8–10 km.

In the period 1992–1995 the water table, or more precisely the recharge conditions influencing the water table, changed significantly (Bárdossy and Molnár, 2003b). Up to 1991, the Danube was a source of recharge to the shallow-groundwater, whereas following the diversion the abandoned main riverbed taps the shallow-groundwater (Hankó et al., 1998).

The Mosoni branch of the Danube has significantly less influence on the modification of the shallow-groundwater level as compared to the main channel. Water table measurements in monitoring wells indicate that such a relationship exists only in the southeastern area of Lower-Szigetköz. Furthermore, the effects of the River Rába and the dammed Danube cannot be ignored in this area.

Since the diversion of the Danube, the previously hydrodynamically quasi-homogeneous area split into three different parts with respect to the changes in the shallow-groundwater level. In the upper-part of the Szigetköz, at the vicinity of the Čunovo (Dunacsúny) reservoir, the water level of shallow-groundwater increased. Between Dunakiliti and Palkovičovo (Szap) the level of shallow-groundwater decreased (Middle-Szigetköz). The third part (Lower-Szigetköz) is below the confluence of the Gabčikovo/Bős conveyance canal and the original Danube bed; hence, the diversion of Danube caused no effect on the shallow-groundwater.

Studies of shallow-groundwater level in the Szigetköz started in the early 1950s with the setting up of a network of groundwater monitoring wells. The positioning of this series of wells was perpendicular to the Danube, and they were capable of monitoring the uppermost gravel layer only. The diversion of the Danube from 1992 onwards, i.e. from the coming on stream of the Gabčikovo (Bős) hydroelectric power plant, created drastic changes in the water level fluctuation patterns of the groundwater table.

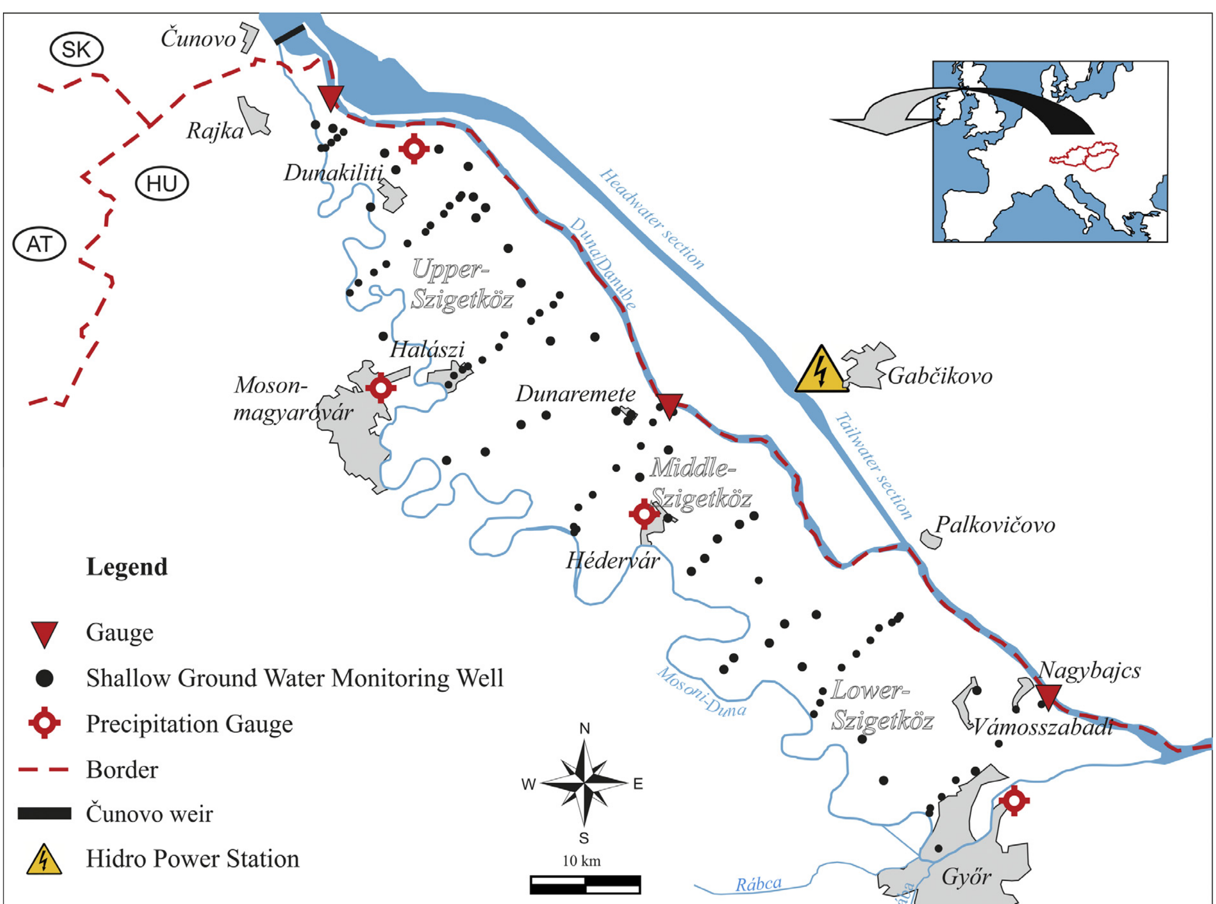

Fig. 1. Location of the study area.

The detection of changes due to the disturbed water flow regime of the Danube is not at all a straightforward task, because a number of natural and man-made processes influence the fluctuation of the shallow-groundwater level. The canals and rivers in the study area control the natural random fluctuations in the water table, either feeding or draining the shallow-groundwater, depending on their own water level. Another influencing factor is the recharging of subsurface water by precipitation, while water withdrawals by communities constitute an artificial influence. In order to distinguish the effect of the Danube from this latter effect, the corresponding data was needed. Annual precipitation varied from 570 to 583 mm in the period 1953–2002. Honti (1955) and Ubell (1959) claim that in the Szigetköz area infiltration from precipitation is negligible when compared to recharge from the Danube, while other sources (Újfaludi and Maginecz, 1993) state that infiltration from precipitation is only one order of magnitude less than recharge from surface water.

Among the other factors influencing the level of the water table, the drawing of water for public use alone may have significance. The majority of the wells used for this purpose are shallower than 130 m, and they are filtered by a Pleistocene gravel series with a high hydraulic conductivity.

Considering the above-mentioned facts, a mathematical model needs to be formed on the basis of probability theory. Data provided by the monitoring wells are considered as *time dependent random quantities*, so the hydrographs of each well are regarded as realizations of stochastic processes. Processes pertaining to the wells are not separate phenomena, but the occurrence of the same natural phenomenon under different local conditions. That is why it is natural to treat these processes as the components of a multidimensional course, and as a matter of fact these components are probabilistically interdependent. It has to be emphasized that this interdependence is related to a spatial structure, and then the data are interpreted as the realization of a one one-dimensional but space–time dependent stochastic process. However, it is not the aim of the study to analyze the dynamics of this spatiotemporal process in full.

The hypothesis is that the observed processes at different locations are governed *by the same essential impacts*, such as recharge from precipitation and rivers and water drawing, while the *intensities* of these impacts *depend on locality*, serving as the main source of spatial dependence. Thus, the realization of the aim can be achieved by identifying these impacts, and determining their spatially dependent intensities. In order to decompose the hydrograph time series into the linear combination of the influencing effects – called factors – dynamic factor analysis has been applied.

2. Material and methods

2.1. Used dataset

In view of the events and alterations made to the Danube it was inevitable that the two time periods before (1953–1991) and after (1993–2002) the diversion should be studied. For the period 1953–1991, the time series of 43 groundwater monitoring wells were registered with sufficient frequency and regularity in order to suit the purposes of our analysis, while for 1993–2002 90 groundwater monitoring wells with adequately registered data were selected. In the analyses described below these two groups of 43 and 90 wells respectively were used consistently when referring to the time periods as above. These provided the response data. At the beginning of the time interval these were sampled twice a week, while after the diversion of the Danube in certain wells the temporal sampling frequency increased to hourly measurements. The explanatory parameters were the water level in the Danube, measured daily on three gauges (Rajka, Nagybajcs, Dunaremete), and precipitation, measured daily at four meteorological stations located 10 to 20 km from each other in the area (Mosonmagyaróvár, Hédervár, Dunakiliti, Győr-Likócs). In the last decade the monitoring network has been significantly altered, furthermore a complex system consisting mainly of a network of canals has been developed to prevent the decrease in the shallow-groundwater reserves and further ecological damage. This prevention network primarily has increased drastically the influence of local effects and this, coupled with the decrease of permanent data sources makes it difficult, and in some subareas even impossible to recognize the regional effects. This is the reason why the use of data available after 2003 was abandoned.

The main criterion in the selection of the gauges and the shallow groundwater wells was the overlapping time interval. In particular, the need for measured data during the whole time interval investigated (1953–1991 & 1993–2002). The used datasets were acquired from the VITUKI (Environmental and Water Management Research Institute) and the calculations were carried out using the program developed by Michaletzky, Tusnády, Zierman and Bolla and IBM SPSS Statistics 19.

2.2. Dynamic factor analysis

Often the statistician encounters measurements of a very complex, but readily-observable time-dependent random phenomenon that is induced by only a few basic, but unobservable (latent) effects of a relatively simple dynamic structure. The behavior of the measured phenomenon can be understood much better when these common driving forces are identified. In the conventional setup when independent observations are at hand factor analysis provides the variables representing the latent effects. As Anderson (1963) warns, this technique can be misleading when applied to multidimensional time series with delayed interdependence among its components. Time-lagged interdependence invalidates the results of conventional factor analysis which has been elaborated for independent observations. Correct identification of the governing effects became possible with the invention of *Dynamic Factor Analysis* (*DFA*), which is capable of taking into account the dynamic structure of both observations and factor time series.

The term *dynamic factor analysis* goes back to the pioneering work of Geweke (1977). Shortly afterwards a number of different concepts and procedures, all of them being generalizations of this or that properties of the conventional factor model, became known as dynamic factor analysis. For example (Picci and Pinzoni (1986a,b), Van Schuppen and Van Putten (1985) generalize the known property that observations are conditionally independent given the factors. Others, like Deistler and Scherrer (1991) decompose in every frequency the spectral density matrix function as the sum of a diagonal and a singular matrix. So, by constructing factor spectral densities, they produce realizations of the factor time series on the basis of the observed realizations. Gourieroux et al. (1995) and Gourieroux and Monfort (1997), consider factor representations for Markov-processes. These, as well as other early contributions to the literature on dynamic factor models like Sargent and Sims (1977), Engle and Watson (1981), Watson and Engle (1983), Connor and Korajczyk (1993) and Gregory et al. (1997), consider time series mostly with limited panel dimensions. Factor models for spatio-temporal processes have also become a focus of interest, see e.g. Mardia et al. (1998).

The increasing availability of high-dimensional data sets has intensified the quest for computationally efficient estimation methods, leading to a renewed interest in dynamic factor analysis. DFA consolidated into state space representations of structural time series models. The new wave of literature was headed by

Forni et al. (2000), Stock and Watson (2002) and Bai (2003). These methods are typically applied to the high dimensional panels of time series. Exact maximum likelihood methods, such as that proposed in Watson and Engle (1983), have traditionally been dismissed as computationally too intensive. However, Jungbacker and Koopman (2008) present new results that allow the application of exact maximum likelihood methods to large panels. Examples of recent papers employing likelihood-based methods for the analysis of dynamic factor models are Doz et al. (2006) and Reis and Watson (2007).

Although the method is not as widespread as its applicability in hydrology and hydrogeology would lead us to believe, there have been studies which have dealt with similar phenomena. When it comes to the application of DFA, there are two known cases when it is applied: (1) when only one parameter was sampled at many sampling sites, as in this case (see e.g. the studies of Kovács et al., 2004; Márkus et al., 1999), and (2) in the reverse situation, when the time series of multiple parameters are assessed together at only one sampling site (Hatvani et al., 2014). Naturally, in certain fortunate cases multiple sampling sites and parameter time series could be explored together (Kaplan et al., 2010; Muñoz-Carpena et al., 2005; Ritter and Muñoz-Carpena, 2006).

3. Calculation

The dynamic factor model briefly described in the present paper does not differ much from those based on state space representation, but the algorithmic solution relies on different concept. The idea, as it is currently used, originates in the work of Bánkövi et al. (1979), though it also relates to that of Box and Tiao (1977) on canonical transformations of time series vectors. While prescribing an autoregressive structure to the factor time series our factor analysis model minimizes a cost function, which is a linear combination of the conditional variance of the prediction error and the state estimation error. The problem of finding the optimal factors leads to a minimization problem on Stiefel manifolds, which have been much in focus in recent investigations in operational research (see e.g. Rapcsák (2002)). The theoretical solutions are very complex and difficult to give, the explicit solutions hardly go as far as 10 dimensions, thus falling far short of our case. So, this optimization problem can instead be solved by an iterative method, which relies on the maximization algorithm of sums of heterogeneous quadratic forms developed in Bolla et al. (1998).

The general aim of factor analysis is the decomposition of the observed data into the superposition of global effects – i.e. effects that influence all or almost all observations, although to different extents – plus an idiosyncratic component, for each individual observation, representing all local "effects" including (but this does not exhaust the list) the heterogeneity of the environment within which the global effects have to exert their influence.

Let us consider the usual static factor model equation

$$Y = \mathbf{A} \cdot F + \varepsilon \tag{1}$$

expressing that the observations Y are described by linear combinations of several latent factors F plus a random uncorrelated noise ε. Usually, the number of observed variables, N, is significantly higher than that of the factors, M. The crucial difference when dynamic factor models are considered is that both observations and factors are empirical time series instead of independent samples/measurements of the variables, as is the case in ordinary models. To complete the model, the dynamic structure of the factors has to be specified. The linear transformation expressed through the $\mathbf{A}$ matrix, however, should not depend on time. Supposing the observed N-dimensional time series

$$Y(t) = (Y_1(t), \ldots, Y_N(t))', \quad 0 \le t \le T.$$

to be weakly stationary apart from a possible linear trend, and emphasizing time dependence rewrite (1) as

$$Y(t) = \mathbf{A} \cdot F(t) + \varepsilon(t) \tag{2}$$

with the $\mathbf{N} \times \mathbf{M}$ matrix $\mathbf{A}$, the factor time series vector

$$F(t) = (F_1(t), \ldots, F_M(t))', \quad 0 \le t \le T,$$

of M *uncorrelated, stationary* time series, and the N-dimensional Gaussian white noise

$$\varepsilon(t) = (\varepsilon_1(t), \ldots, \varepsilon_N(t))', \quad 0 \le t \le T.$$

The aim is to find optimal, in a certain sense, *estimations* of the factors:

$$\hat{F}(t) = \left(\hat{F}_1(t), \ldots, \hat{F}_M(t)\right)'$$

The estimation of our model should focus on the following three natural requirements:

(i) The estimation of the factors should be a *time-independent* homogeneous linear transformation of the observations.

$$\hat{F}(t) = \mathbf{B} \cdot Y(t) \tag{3}$$

(ii) The factor time series components $F_j(t)$ should be linearly reliably predictable from their past. This requirement is certainly fulfilled if we suppose them to be *autoregressive* processes of order L_j with a constant included in the autoregression:

$$F_j(t) = c_{j,0} + \sum_{k=1}^{L_j} c_{j,k} \cdot F_j(t-k) + \delta_j(t) \tag{4}$$

where the components of the Gaussian white noise $\delta(t) = (\delta_1(t), \ldots, \delta_M(t))'$ are independent from each other and from $\varepsilon(t)$.

(iii) Again, time-independent linear transformation of the factors should provide a "good" estimation – called the factor-estimator – of $Y(t)$, as expressed by the equation

$$\hat{Y}(t) = \mathbf{D} \cdot \hat{F}(t) \tag{5}$$

where the $\mathbf{D}$ matrix is in fact the estimation of $\mathbf{A}$.

The choice of autoregression in (ii) is justified not only by its simple dynamic structure, but also by the fact that the hydrographs of monitoring wells can reliably be modeled by autoregressive processes. In the process of model estimation it is supposed that the structure prescribed for the *unobservable factors* is passed on to its *estimations*. Were the components of $(\hat{F}_1(t), \ldots, \hat{F}_M(t))$ observable, their *best forecast* $\tilde{F}_j(t)$ could be obtained as

$$\tilde{F}_j(t) = c_{j,0} + \sum_{k=1}^{L_j} c_{j,k} \cdot \hat{F}_j(t-k) \tag{6}$$

In order to relate $\tilde{F}_j(t)$ to $F_j(t)$, we call $\tilde{F}_j(t)$ the empirical best forecast of $F_j(t)$. In other words, it is just the plug in of the predicted factors into the best forecast of the autoregression. As the true values are not known, the coefficients $c_{j,k}$ have to be estimated. The optimality of this forecast, guaranteed for a truly autoregressive process with known coefficients only, cannot in general be preserved for the plug in. Keeping this in mind, we will use (6) for the forecast of the estimator $\hat{F}(t)$ given its past. Since the observations, and thus the predictions of the factors, can be computed for all $t, 0 \leqslant t \leqslant T$, it is possible to compare the forecast with the estimator itself, and by centering, get an unbiased estimation $\hat{\delta}(t)$ of the noise $\delta_j(t)$ in (4) as

$$\hat{\delta}_j(t) = \tilde{F}_j(t) - \hat{F}_j(t) - \left[\overline{\tilde{F}_j - \hat{F}_j}\right].$$

(For any $X(t)$ $\bar{X}$ denotes the average $\frac{1}{T+1}\sum_{t=0}^{T}X(t)$). The squared sum $\varepsilon^{(d)}$ of $\hat{\delta}_j(t)$ is called the estimated *dynamic error*:

$$\varepsilon^{(d)} = \sum_{j=1}^{M}\sum_{t=L_j}^{T}\hat{\delta}_j(t)^2.$$

Similarly, $\hat{Y}(t)$, the factor-estimator of observations in (5), opens the way to estimate $\varepsilon(t)$, the noise in (2), by taking the centered difference as

$$\hat{\varepsilon}_i(t) = Y_i(t) - \hat{Y}_i(t) - \overline{\left[Y_i - \hat{Y}_i\right]},$$

the squared sum of which is called the predicted static error, denoted by $\varepsilon^{(s)}$:

$$\varepsilon^{(s)} = \sum_{i=1}^{N}\sum_{t=0}^{T}\hat{\varepsilon}_i(t)^2.$$

If the importance of this or that observation is to be emphasized, or the precision of the forecast of this or that factor is of major concern then *weights* can be introduced into the definition of both dynamic and static errors to achieve this end. To fulfil the requirement given in (iii), the estimation of the model is regarded as "good" if the sum of the estimated static and dynamic errors is minimal. This means the minimization of the following functional:

$$\Psi(T) = \varepsilon^{(s)} + \varepsilon^{(d)} = \sum_{i=1}^{N}\sum_{t=0}^{T}\hat{\varepsilon}_i(t)^2 + \sum_{j=1}^{M}\sum_{t=L_j}^{T}\hat{\delta}_j(t)^2 \quad (7)$$

on the constraints,

$$\mathrm{var}(\hat{F}) = I_M \quad (8)$$

stemming from the uncorrelatedness of the factors (I_M denotes the $M \times M$ unit matrix).

The real statistical difficulty lays in the estimation of the model parameters, that is the matrices **B**, **C**, **D**. Remark, that **C** is the matrix of $c_{j,k}$-s from (4) endowed with zeroes when necessary.

The usual ML methodology results in very complicated computations, and even though one can determine the density function, it seems rather hopeless to find its place of global maximum. In state space models the EM algorithm provides a way of tackling the estimation problem. Alternatively, Markov Chain Monte Carlo (MCMC) estimation may also prove to be viable.

Our approach originates in Bánkövi et al. (1979), where instead of finding a direct optimal solution to (7) and (8) an iterative approximation using a criss-cross algorithm is suggested. It can be developed further by using the optimization procedure of heterogeneous quadratic forms as described in Bolla et al. (1998), where the analysis of the optimization can also be found. For a detailed description see Ziermann and Michaletzky (1995) or Márkus et al. (1999).

Introducing a new appropriate orthonormal system $\{\mathbf{e}_j\}_{j=1,\dots,M}$ as in Márkus et al. (1999), the functional, rewritten as $\Psi = \sum_{j=1}^{M}\mathbf{e}_j^T\mathbf{Q}_j\mathbf{e}_j$ with the $\mathbf{Q}_j$ matrices computable from the observations and the **C** matrix, has exactly the same structure – that is the sum of heterogeneous quadratic forms – as the one treated in Bolla et al. (1998). By applying Lagrange's multipliers it is easy to obtain a necessary condition for the existence of stationary point, namely that the equation

$$[\mathbf{Q}_1\mathbf{e}_1, \dots, \mathbf{Q}_M\mathbf{e}_M] = [\mathbf{e}_1, \dots, \mathbf{e}_M]\mathbf{S}$$

must hold with **S** being a symmetrical $M \times M$ matrix. Specifically the vectors $\mathbf{Q}_j\mathbf{e}_j$ are included in the subspace spanned by $\mathbf{e}_1,\dots,\mathbf{e}_M$.

For the place of global maximum $\mathbf{S} \geqslant 0$ holds. Introducing the notations $[\mathbf{e}_1, \dots, \mathbf{e}_M] = \mathbf{E}$, $[\mathbf{Q}_1\mathbf{e}_1, \dots, \mathbf{Q}_M\mathbf{e}_M] = \mathbf{Q}(\mathbf{E})$ and writing the condition formally, we have

$$\mathbf{Q}(\mathbf{E}) = \mathbf{ES}, \quad \mathbf{E}^T\mathbf{E} = \mathbf{I_M}, \quad \mathbf{S} \geq 0,$$

which is nothing, but the polar decomposition of the matrix $\mathbf{Q}(\mathbf{E})$. A one to one correspondence of the polar, and the singular value decompositions is established in Bolla et al. (1998) and a criterion for $\mathbf{S} \geqslant 0$ i.e. **S** being positive semidefinite is also given there. So, the actual computations rely on the singular value decomposition instead of the polar one. It seems that this is the computationally most demanding step of the algorithm, and sometimes it does not converge fast enough.

Summarizing, the algorithm is as follows. For a given $\mathbf{E}_1 = \mathbf{E} = [\mathbf{e}_1, \dots, \mathbf{e}_M]$ vector system the next one $\mathbf{E}_2 = \mathbf{H} = [\mathbf{h}_1, \dots, \mathbf{h}_M]$ is defined from the polar decomposition of $\mathbf{Q}(\mathbf{E})$ by

$$\mathbf{Q}(\mathbf{E}) = \mathbf{HS}, \quad \mathbf{H}^T\mathbf{H} = \mathbf{I}_M, \quad \mathbf{S} \geq 0.$$

It can be shown – as it is in Bolla et al. (1998) – that the algorithm increases the value of the Ψ functional, and the $\mathbf{E}_1, \mathbf{E}_2, \dots$ matrices are getting closer and closer to each other, and so the accumulation points of the algorithm are their stationary points as well. The set of accumulation points is a connected one. If any point obtained from the algorithm falls "near" to the place of global maximum then the algorithm will be *convergent*, and it will converge to this *place of global maximum*. However, the algorithm is not necessarily globally convergent, because in general there may exist fixpoints of it different from the place of global maximum. Every stationary point of the functional is a fixpoint of it at the same time.

4. Results and discussion

The first step in the analysis of the data described in the introduction was to characterize the hydrograph time series of the monitoring wells in the area. Hydrographs were grouped using cluster analysis on the annual mean values (Ward's method, squared Euclidian distance). Cluster analysis is a widely used method to group observations based on their similarity (Cloutier et al., 2008; Hatvani, 2010). Then a discriminant analysis was carried out to check its correctness. The 43 monitoring wells active for the period 1953–1991 were clustered into 3 groups. Fig. 2 depicts the hydrographs of wells belonging to the same group, while Fig. 3 shows the spatial distribution of the wells. The wells in groups 2 and 3 have compact locations, while wells in group 1 are scattered all over the study area.

For the period 1993–2002 the 90 studied wells were divided into four major groups based on the characteristic pattern of the time series. Fig. 4 shows the hydrographs of wells according to groups. The wells belonging to group 1 fluctuate somewhat heterogeneously; four of them belong more closely together, but the other three deviate from the main characteristics of the group. Group 2 shows a synchronized wavy pattern without any trend. Group 3 is remarkably homogeneous; only a few hydrographs vary slightly from the main pattern between 1997 and 2002. The dynamic increase of water level between 1994 and 1996 and the following decreasing trend mark this group. The pattern of group 4 is similar to that of the previous group. However, the hydrographs of group 4 do not feature the water level drop between 1993 and 1994, and they display a more pronounced water level decrease after 1996. Fig. 5 depicts the spatial allocation of the wells of the four groups. The wells of group 1 are scattered mainly around in the Lower-Szigetköz. The wells of group 2 are located in connected areas of the southern part of Lower-Szigetköz. The wells of group 4 cover the major part of the Szigetköz, while the wells of group 3 are located in the north – northeastern part of the Szigetköz and in the Upper-Szigetköz. It can be stated that there are characteristic patterns of the hydrographs for both periods, and the spatial distribution of wells with a given hydrograph pattern marks definite subareas of the Szigetköz.

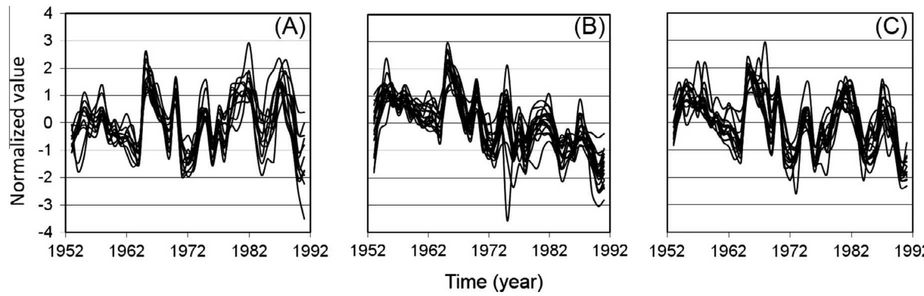

Fig. 2. Standardized hydrographs of monitoring wells of Groups in the period 1953–1991.

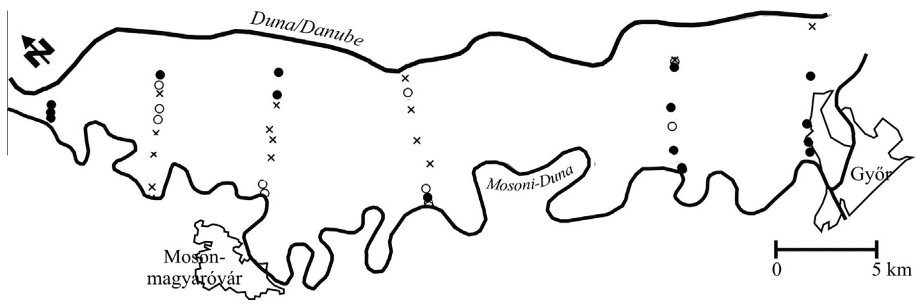

Fig. 3. Spatial allocation of monitoring well groups in the period 1953–1991 (O: group 1; ●: group 2; X: group 3).

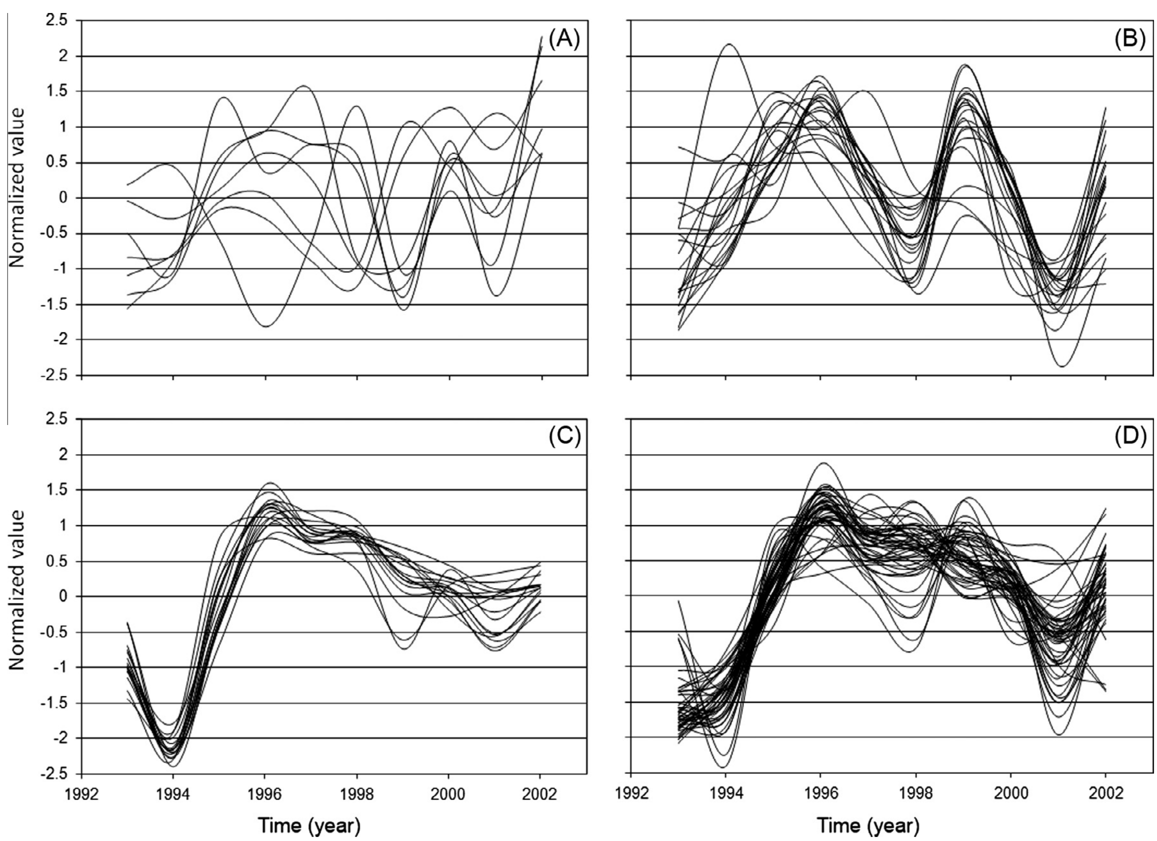

Fig. 4. Standardized hydrographs of monitoring wells in the period 1993–2002 for group 1 (A); group 2 (B); group 3 (C); group 4 (D).

4.1. Factors driving the groundwater level fluctuations

The changes in recharge conditions caused by the diversion of the Danube are reflected in the groundwater hydrographs (Fig. 4), and in the spatial occurrence of similar hydrograph patterns in the groups (cf. Fig. 5). The effect of the Danube is transferred to the water table through a hydraulically conducting media that transforms it as well. Therefore, a simple regression, which looks for *the same* fluctuation as that of the river level is not appropriate for determining its influence.

In order to single out and analyze the effect of the Danube on the groundwater table independently from other (possible) effects,

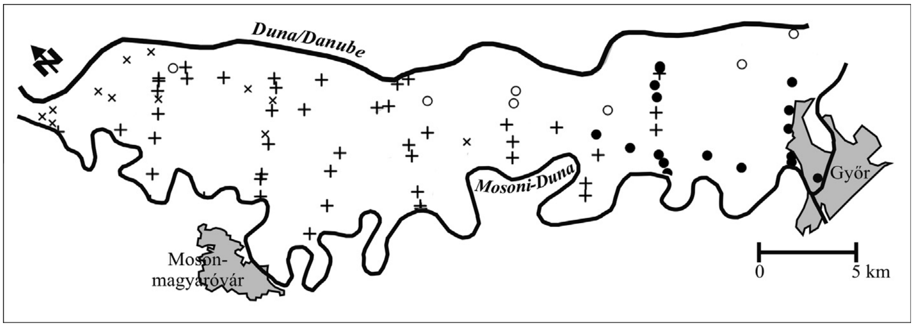

Fig. 5. Spatial allocation of monitoring well groups in the period 1993–2002. (O: group 1; ●: group 2; X: group 3; +: group 4), cf. Fig. 3.

the fluctuation of the water table monitored in the wells has to be decomposed into the influences of factors related to the discharge of the Danube, precipitation, communal water withdrawal, and an individual noise factor that every well possesses of its own. This decomposition is carried out by means of dynamic factor analysis applied to the annual mean groundwater level data. When the dynamic factor time series are obtained their interpretation and identification follows.

As to the number of factors, there are several methods which should be mentioned. Beyond the well elaborated tools of conventional factor analysis, for dynamic cases Peña and Box (1987) suggests the estimation of the number of factors based on the eigenvalues of the time delayed covariance matrix. King et al. (1994) include factors as long as the specific variance of the last one equals to zero. In general these methods suggest extracting more than 3 factors. Nonetheless, from the practical point of view it did not seem plausible to have more factors, because they could not have been identified. However, there may still remain some common sources of variance that are perhaps related in some way to the hydraulic properties of the top layer, but at the moment no quantified information is available with which these effects could be compared.

Both the Akaike and the Bayes information criteria pointed to 1st order autoregression in the vast majority of the observations, so, choosing higher order for the factors did not seem plausible. Choosing any of the three factors to be white noises resulted in much more significantly autocorrelated residuals. Hence, an AR(1) structure for each of the three factors seemed to be the best choice.

The factors were computed by the iterative approach described above. The procedure was declared convergent when the difference of the Ψ-functional value was less than 0.001 in two consecutive steps. As there was no reason to emphasize the significance of either a monitoring well or a factor, equal dynamic and static weights were used in the Ψ-functional.

4.2. Identifying the factors as latent effects governing the monitored wells

Dynamic factor analysis produces factor time series as an output; these series must then be identified with those processes of Nature that influence or drive the analyzed phenomenon. For the unambiguous identification of the calculated factors properly registered data of the driving effects are also necessary, and unfortunately, only annual total water withdrawal data are available for the period of 1993–2002. The analysis was performed for the periods before and after diversion as well, keeping the temporal division.

To go beyond the temporal aspect and infer the spatial structure, too, another output of the dynamic factor analysis, i.e. the factor loadings, is to be used. The factor loadings measure the intensity of a given factor at a location. Hence, it is possible to use them in quantifying the intensity of the effects at a given monitoring location then extend it to arbitrary locations by composing a map of the intensity of a given factor. The map may be created by standard geostatistical procedures (e.g. kriging).

4.2.1. The period before diversion: 1953–1991

The first dynamic factor, determined from the 43 monitoring wells for 1953–1991, is closely related to the water level fluctuation of the Danube (Table 1). Fig. 6 displays the time series of factor 1 and of the water levels of the Danube measured at Rajka and Nagybajcs in the given time period. Table 1 shows the corresponding correlations.

The annual total precipitation averaged for four measuring gauges (Mosonmagyaróvár, Hédervár, Dunakiliti and Győr-Likócs) has a correlation of 0.66 with factor 1. This result was to be expected, as the water level of the Danube also has significant correlation with the precipitation – though it is lagged when observed on a more frequent time-scale. The calculated factors 2 & 3 do not correlate either with the water level in the Danube or with the annual precipitation of the stations. One can draw the conclusion that factor 1 is the effect of the water level of the Danube. Furthermore, the effect of the Danube on the shallow-groundwater fluctuation is the most significant factor, and it suppresses the impact of all other background factors.

4.2.2. The period after diversion: 1993–2002

When applied to the 90 suitable hydrographs of 1993–2002 dynamic factor analysis yields a first factor which again corresponds to the water level of the Danube. However, higher correlations (0.83) can only be found between factor 1 and the *average* of the measurements of the two stations (Rajka and Dunaremete). The reason is that after the diversion of the Danube, its water level is regulated by humans and not by nature. As a consequence, water level fluctuation is different at the measuring stations. At the Rajka station, the submerged weir (built in 1995) increased the water level and kept it at a fixed level, while at Dunaremete, not far above the confluence of the old riverbed and the power-plant canal, a new natural regime is formed by the back-swelling of water in the smaller, old river branch, the overspill of the weir and some local water fluctuations. The groundwater table created over the

Table 1
Correlation between factor 1 and the measured water level of the Danube at Rajka and Nagybajcs (1953–1991).

Gauge	Correlation
Danube at Rajka	0.972
Danube at Nagybajcs	0.948

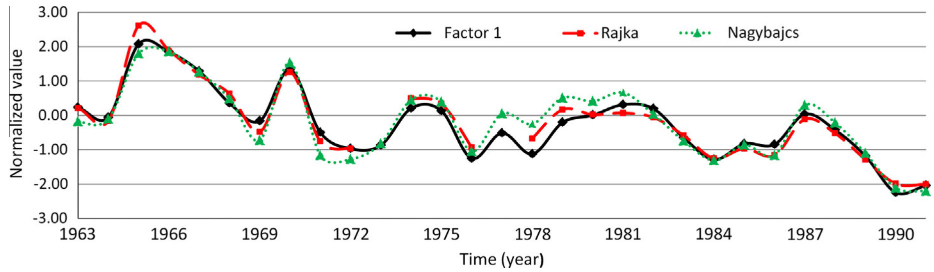

Fig. 6. The first dynamic factor and the measured water level of the Danube at Rajka and Nagybajcs, from 1953 to 1991.

whole area is the result of the recharge from the complete river section which lies between the two gauges, so the average of the two measurements describes best, though not perfectly, the temporal variation of the water table (cf. Fig. 7). In the diverted Danube section, after the diversion the water flow decreased thus smaller sediment fractions were settled on the river bed. This way the "communication" between shallow groundwater and the river was retained. This is reflected in the decrease of the factor (1999–2001), while in 2002 the heavy floods washed out this sediment layer, giving ground for the river water to reach once more the shallow groundwater. As a result, factor 1 increased its alignment with the water levels of Rajka and Dunaremete.

Precipitation seems to be a natural choice to consider as an influencing effect, and the computed second dynamic factor can indeed be identified with it. Table 2 shows the correlations between factor 2 and the annual total precipitation at the gauges. These correlations are higher than 0.82, except for the one at Mosonmagyaróvár. The latter discrepancy might be caused by the outlier value in 1998. Fig. 8 shows the time series of factor 2 and the rescaled measured precipitation at the four gauges. As compared to the period 1953–1991, an important difference is that precipitation is now a detectable factor, while it did not appear to be identifiable or distinguishable from the Danube in the first period. The reason is for this that the sources of recharge of the groundwater in Szigetköz changed after the diversion of the Danube. On the one hand, the extent of the river-effect decreased significantly, and in exchange, the relative influence of the precipitation increased. On the other hand, as a result of human interference the temporal courses of precipitation and water level in the river diverged and hence became detectable in different factors.

The calculated third factor closely relates to the time-series of the Danube water level at Nagybajcs, the correlation is 0.83. This station is located below the confluence of the power plant canal and the main channel of the Danube. Therefore, the water level in the Danube is close to the "natural" one, though modified by the damming of the hydroelectric power plant. This part of the Danube influences the groundwater recharge of Lower-Szigetköz, so it is a separate background effect with a separate temporal course. Hence, it is not surprising that dynamic factor analysis selects it in the form of the calculated third factor, as a separate effect. Fig. 9 compares the normalized values of the two time series, the registered data of Nagybajcs gauge and the third factor.

Table 2
Correlation between factor 2 and the cumulated precipitation at 4 locations of the study area.

Precipitation station	Correlation
Győr-Likócs	0.82
Mosonmagyaróvár	0.58
Dunakiliti	0.84
Hédervár	0.83
Average precipitation	0.82

4.3. Spatial distribution of the dynamic factor loadings

The factor loadings, an integral part of dynamic factor analysis, represent the relative intensity of the effects – corresponding to the factors – at a given location. In other words, the factor loadings give the weights of individual effects at a given location that combine them into the phenomenon observed there. As such, the loadings do not depend on time, but they do depend on location. By the usual interpolation techniques, such as kriging, the map of dynamic factor loadings – one map for the loadings of each factor – can be created, in this way extending the information obtained from observation sites to any location in the area. This was done in our analysis for both time periods studied.

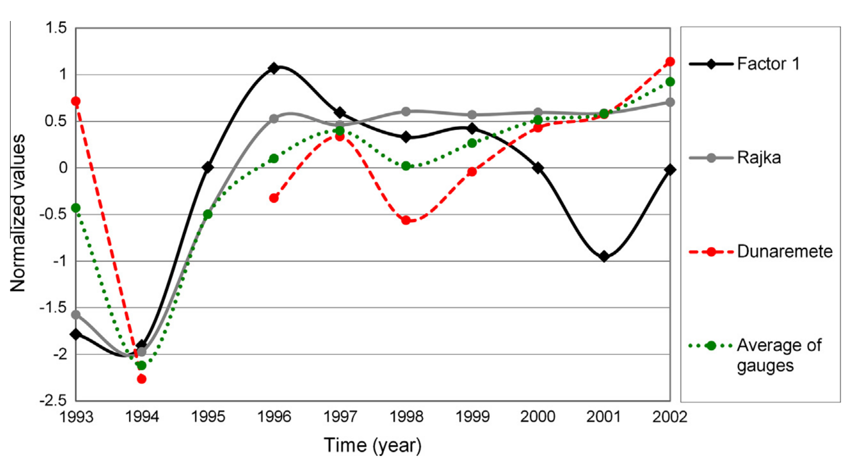

Fig. 7. Factor 1 and the standardized water level of Danube at Rajka and Dunaremete, 1993–2002.

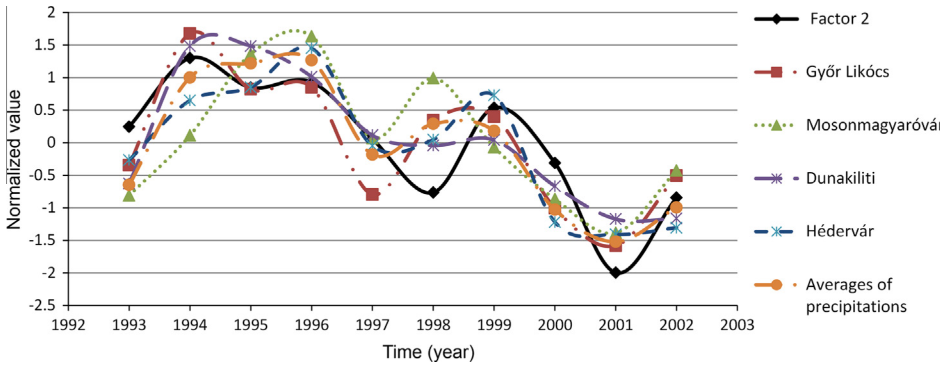

Fig. 8. Factor 2 and the standardized value of precipitation, 1993–2002.

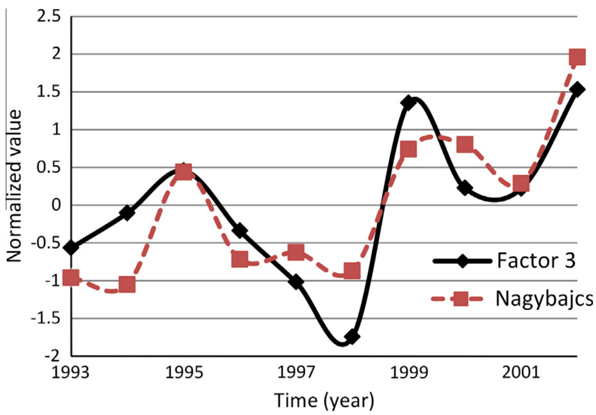

Fig. 9. Factor 3 and the standardized water level of the Danube at Nagybajcs, 1993–2002.

4.3.1. The period 1953–1991

Fig. 10 shows the spatial distribution of the loadings of the first dynamic factor determined for the period 1953–1991. It should be noted that the area is covered by 41 monitoring wells, and this fact influences the resolution of the map. By and large, the isolines of the factor loadings run parallel to the Danube. The highest loadings occur at the third northwest–southeast well-series at Halászi. There are further high values at Győr, the town at the confluence of the rivers Mosoni-Danube and Rába. The hydrogeological interpretation of this fact is that in the vicinity of this area the recharge from the rivers was highest before diversion.

4.3.2. The period 1993–2002

The spatial distribution of the loadings of factor 1 (Fig. 11) in the period 1993–2003 differs significantly from that of the previous time-period. Now the first factor represents the effect of the watercourse of the river, regulated by human interference. The factor loadings are higher in the Upper-Szigetköz (North-West), and this is the only area adjacent to the Danube where the factor loadings are high. The most noticeable change is that the high values of loadings have moved downstream from Halászi, from the third series of monitoring wells, to the next, fourth series at Dunaremete. There are particularly high factor loadings in the northwestern corner of Szigetköz and in the vicinity of the submerged weir at Dunakiliti. In the inner part of the Upper-Szigetköz the factor loadings are smaller, reflecting the fact that as we move farther away from the river, its effect decreases. In Lower-Szigetköz, near the confluence of the Danube and the power plant canal, the factor loadings are the smallest. This is in line with the expectation that the effect of human interference wanes as we move away from the location of that interference. There is a similarity here to the previous period, in that the loadings values are relatively high in the vicinity of Győr compared to other areas. The overall magnitude, however, is significantly lower than in the previous period. It is also true for the whole area that the overall magnitude of the loadings of the first factor are lower in the second period than in the first one. This may indicate that the first factor explains less variance in the second period than in the first.

The amount of water passing through the main channel by the regulation of the Čunovo-reservoir determines the fluctuation of the river level between the 1852 and 1843 river km. The submerged weir built at 1843 river km dams up the water in the main channel, so a stabilized water level with very low fluctuation characterizes this river section. Below the weir the spill-over and the channel bed morphology determine the water level of the river. When the water diverted through the power-plant canal reenters the Danube it swells back and causes silting between 1820 and 1811 river km (Rákóczi, 2012), and as a consequence, the hydraulic

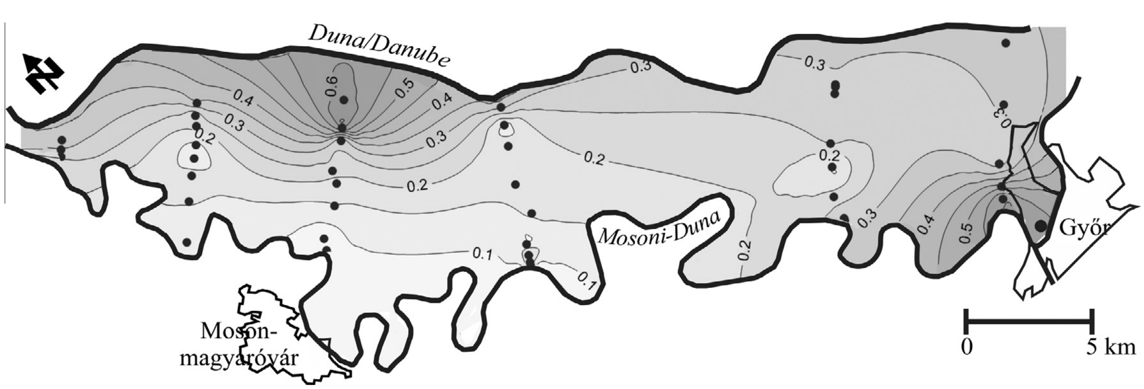

Fig. 10. Spatial spread of the loadings of factor 1 determined for the period 1953–1991. The position of monitoring wells are marked with black dots.

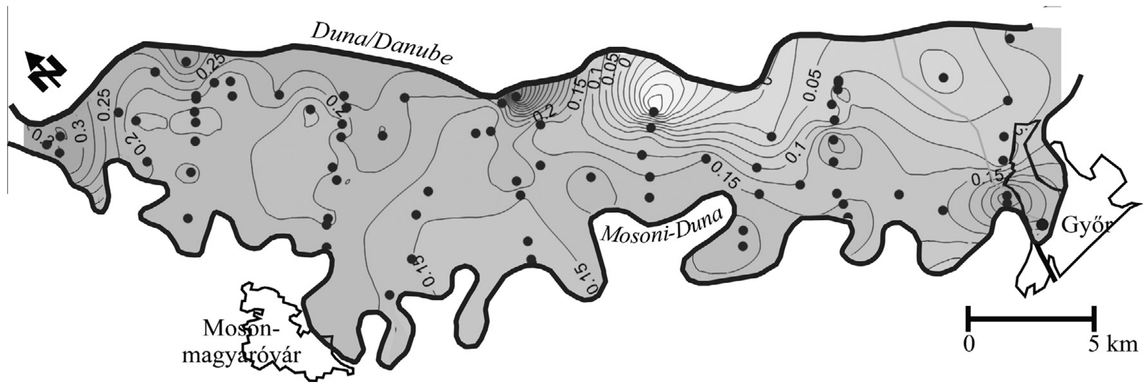

Fig. 11. Spatial spread of the loadings of factor 1 determined for the period 1993–2003. The position of monitoring wells are indicated with black dots.

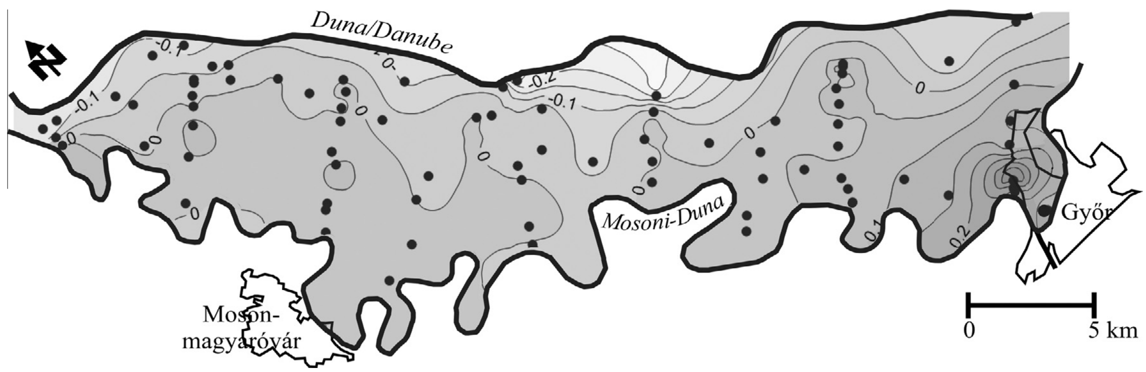

Fig. 12. Spatial spread of the loadings of factor 2 determined for the period 1993–2003. The positions of monitoring wells are indicated with black dots.

conductivity of the channel bed has decreased. This prevents the recharge of the groundwater from the river, explaining why the loadings of factor 1 are small here.

We present a map of loadings for the second dynamic factor only for the period 1993–2002 (Fig. 12), since we have not as yet been able to identify the second factor for the earlier period. For the period succeeding the Danube diversion, the second dynamic factor has been identified as the effect of precipitation. Hence, the map of loadings shows the location dependence of the intensity of the effect of precipitation on the shallow-groundwater. In general, it is a very difficult question to determine how great a part of the precipitation reaches the groundwater, and hence in what degree it is "responsible" for its fluctuation. Here, as we calculated the dynamic factor and its loadings directly from the water table fluctuation of the saturated zone in the unconfined aquifer, (and did not use any precipitation data!), the isolines directly represent the relative importance of the precipitation in creating the water table fluctuation. This importance or impact increases with distance from the Danube. The occurrence of the highest values around Győr can probably be explained by the influence of the rivers of Rába and Rábca. Because of their small catchment, not too distant from the monitoring sites, the level of fluctuation of both rivers is closely related to local precipitation, magnifying in this way the precipitation-effect.

The third dynamic factor is identified with the water level of the Danube at Nagybajcs, and the map of its loadings is displayed in Fig. 13. The intensity of this factor is practically zero in the northwestern part of Szigetköz, meaning that this effect does not operate there. Higher values occur only in two areas: one with uniquely high values is at the monitoring wells near Vámosszabadi, close to the Danube, only a few km southeast from the confluence of the power-plant canal and the river. The third factor

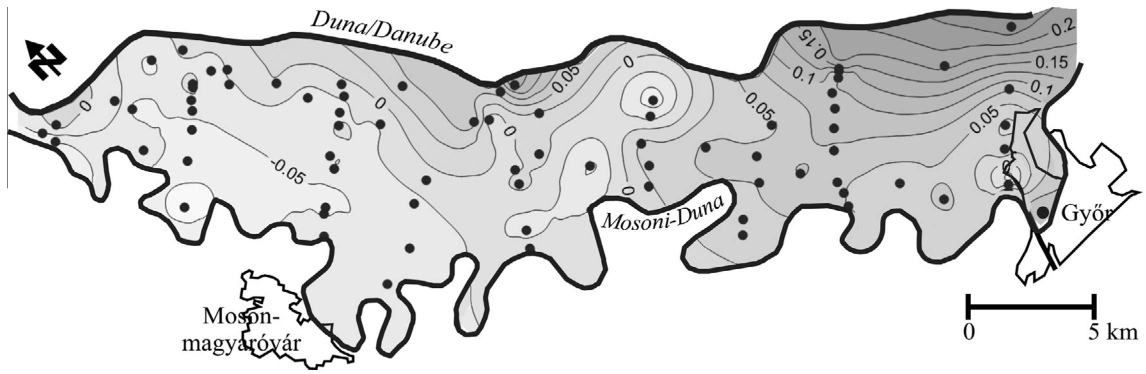

Fig. 13. Spatial spread of the loadings of factor 3 determined for the period 1993–2003. The position of monitoring wells are indicated with black dots.

represents the (more or less) natural course of the river level, indicating that below the confluence the natural course of recharge from the river prevails. The other area is the surroundings of Dunaremete, where the values of the loadings are only half as high as in the previous area and where factor 1 shows maximum values. As both the first and the third factors represent the effect of the Danube, of the regulated and natural courses, respectively, we can claim that the groundwater level in the surroundings of Dunaremete is very sensitive to the changes in the level of the river. This may indicate that hydraulic conductivity is high there. The comparison of the magnitude of the loadings for the two factors clearly point out that the human interference is far more dominant here than the natural course.

Fig. 13 presents the factor loadings map for factor 3, expressing the influence of the waters of the Danube below the confluence of the power plant canal and the old riverbed (as measured at Nagybajcs). This effect is present only in the lower (southeast) section and around Dunaremete and decreases perpendicularly to the Danube.

Changes in the spatial spread of factor loadings may be explained by the fact that the construction of the hydroelectric power plant introduced new factors and modified the role or the proportion of others which determine the fluctuation of water level in different sections of the Danube.

5. Conclusions

In our study we chose to follow a stochastic approach. The stochastic approach represents the various sources of uncertainty as an additive noise component of the process, describing the studied phenomenon. In contrast, calibrated numerical groundwater flow models are usually applied to similar problems. The same uncertainty is inevitably present in these deterministic (or numeric) methods of modeling but it is represented in the uncertainty of the system input parameters, supposed in the models to be constants or smoothly interpolable among observation sites. In the course of stochastic modeling the heterogeneity of the environment is a given uncertainty factor, while in the case of numeric modeling the uncertainty factor is kind of an interpolation error. In addition, numeric models indicate the distribution of the hydraulic head. This however, does not provide information about the explanatory parameter, moreover the explanatory parameters are used as input data and need to be chosen and estimated by the users themselves. The result of the application of the dynamic factor analysis is very useful for reverse modeling. Both approaches have their merits and disadvantages, and when applied with sufficient care and rigor neither of them is superior to the other.

In the area of the Szigetköz floodplain studied, the fluctuation of shallow-groundwater followed a stochastically homogeneous pattern until October of 1992, and it corresponded to fluctuations in the water level of the Danube. From that date onwards, the Gabčikovo/Bős hydroelectric power plant commenced operation, and the majority of the Danube's flow was redirected to a constructed insulated canal. Evidently, as a consequence, a significant change in shallow-groundwater fluctuations followed both in time and space. This fluctuation is a very complex phenomenon, influenced by various factors. Therefore, it is far less evident how it is possible to track those changes back to the effect of the changed flow course of the Danube and how the effect of the river in the whole area can be quantized. The conventional method of determining hidden background effects – in our case the ones that cause groundwater level fluctuation – is factor analysis. Since factor analysis assumes independent observations, which is not the case for water level time series, the dynamic structure and the induced delayed interdependences have to be taken into account as well. Therefore, in such cases the adequate mathematical method is *dynamic* factor analysis.

The hydrographs were decomposed by dynamic factor analysis into a combination of just a few factors plus noise which reconstructs the hydrograph shapes with sufficient accuracy. The factor loadings correspond to the intensity of an effect in the reproduction of the actual hydrograph, and by drawing a map of loadings, the intensity can be interpolated to arbitrary locations of the area, regardless of the availability of observations there. The spatial spread of the intensities quantizes, and the map visualizes the propagation of the influencing effects.

The identification of the factors supports the well-known fact that the shape of hydrographs is determined by water inflow from the river and infiltration. Our analysis goes further, however, by separating out the effect of the river on the shallow groundwater table, thus rendering the cause of the induced changes detectable and the extent of the changes measurable. The novelty and strength of this method can be seen in the fact that it determines the influencing effects by a purely mathematical method from the observed groundwater fluctuation only. Nevertheless the obtained governing forces match the naturally expected effects to a remarkable degree, as observed completely independently from the calculations.

The study has so far explored the influence of the Gabčikovo/Bős hydroelectric power plant and the Ĉunovo reservoir on the environment only in the Hungarian subarea of a greater, hydraulically connected, geologically identical and structurally indistinguishable geological unit. In our opinion this fact calls for the extension of the analysis to the whole area within the framework of a cross-border collaboration with the Slovakian partners.

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