

# Spatiotemporal estimation of land subsidence and ground water level decline in West Thessaly basin, Greece

K. Modis · D. Sideri

Received: 24 January 2014 / Accepted: 12 November 2014 / Published online: 19 November 2014  
© Springer Science+Business Media Dordrecht 2014

**Abstract** Groundwater overexploitation in the Western Thessaly basin resulted to the generation of ground deformations. In order to investigate the mechanism of this phenomenon and of its future occurrences, data regarding the temporal variation of ground deformations and water level were examined and analyzed. They were collected from satellite Persistent Scatterer Interferometry measurements and several water wells, respectively. Based on the above data, the spatiotemporal correlation and cross-correlation of deformations and water level were considered. The modeled cross-variogram indicates a spatiotemporal correlation between the two variables, as would be theoretically expected. This correlation permits the application of cokriging to the deformations with water level as an auxiliary variable. Numerical results are more accurate compared with kriging, as indicated by the decreased estimation errors. The above statistical-based model approach will be useful for spatial interpolation at local and basin scale, while, for temporal estimations, medium-term predictions can be made.

**Keywords** Subsidence · Geostatistical modeling · Space–time cokriging · Space–time cross-variogram · Alluvial deposits

## 1 Introduction

Land subsidence, triggered by excessive groundwater drawdown and resulting from the compaction of the drained loose sedimentary formations, occurred with an increasing rate the last decades throughout Greece (Kallergis 1971, 1973; Andronopoulos et al. 1991). Thessaly plain (Soulis 1980, 1997), is a characteristic example of a region affected by these phenomena (Fig. 1).

---

K. Modis (✉) · D. Sideri  
School of Mining and Metallurgical Engineering, National Technical University of Athens, 9 Heron  
Polytechniou St, 15780 Athens, Greece  
e-mail: kmodis@mail.ntua.gr



**Fig. 1** Damages due to land subsidence in Thessaly basin. The cracks in the stonework on the *left* (photo in 2005 taken by Apostolidis and Georgiou 2007) evolve despite the repairs even 6 years after, as can be seen on the *right* (photo in 2011 taken by the authors)

Civil protection agency of Greece in collaboration with various research Institutions is continuously involved in managing environmental hazards and planning future development of damaged areas. This action requires collection of piezometric measurements and ground deformations data in order to develop detailed maps of their spatial distribution. Estimations of the future values of the above variables are also necessary.

On the other hand, the modeling of spatiotemporal distributions resulting from dynamic processes evolving in both space and time is critical in many scientific and engineering fields. Spatiotemporal models are stochastic models that extend spatial statistics (geostatistics) to include the additional time dimension (Kyriakidis and Journel 1999).

Geostatistical space–time methodology has been applied for modeling spatiotemporal distributions in several scientific disciplines, using a variety of theoretical models from superposition of purely spatial and purely temporal processes, to separable covariance functions (Bogaert and Christakos 1997). These applications include characterization of space–time variability of the Earth’s geophysical parameters (Haslett and Raftery 1989; Seguret and Huchon 1990; Handcock and Wallis 1994; Bogaert and Christakos 1997), modeling of temporal evolution of spatial patterns in soil moisture content (Goovaerts and Sonnet 1993; Papritz and Fluhler 1994; Heuvelink et al. 1997), and estimation of rainfall or piezometric head fields (Bras and Rodrigues-Iturbe 1984; Rouhani and Wackernagel 1990; Armstrong et al. 1993). Thus, the existence of different space–time models allows considerable flexibility in practical applications. The choice and fitting of the appropriate model depends on the natural processes under consideration (Kyriakidis and Journel 1999).

In this work, we apply the geostatistical methodology of space–time ordinary cokriging to deformations and piezometric data, with the aim of producing evidence-based risk maps describing the risk pattern over space and time. Under this two-variable model approach, we model the spatiotemporal continuity via the linear model of coregionalization (Journel and Huijbregts 1978 p. 171). The produced numerical models are useful in the design of preventive and remedial actions against possible land subsidence hazard.

## 2 Geology of the study area

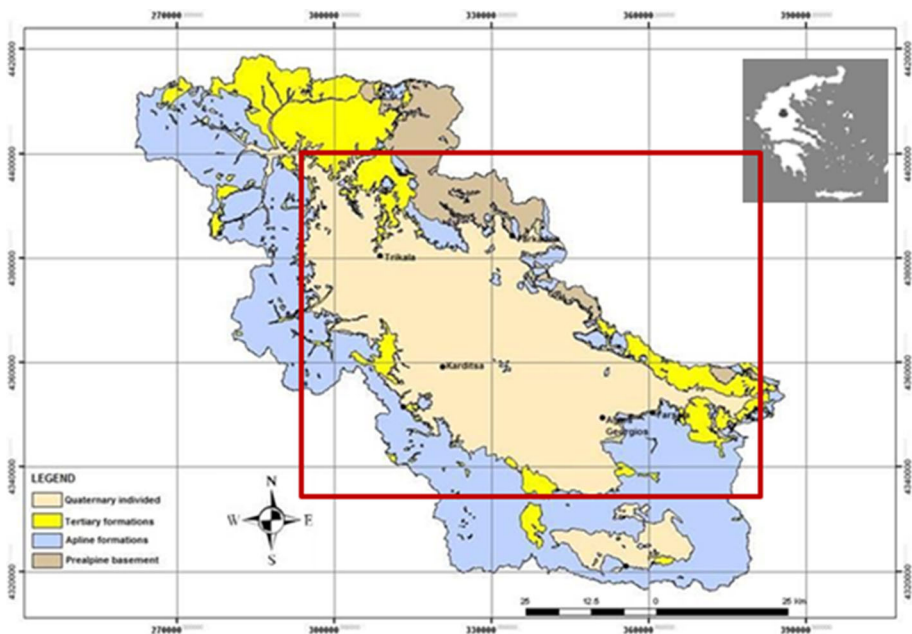
Thessaly basin is a lowland area in Central Greece, of about 4,520 km<sup>2</sup>, mainly drained by Pinios River. The basin is sub-divided by a group of hills into two sub-basins, the Western

and the Eastern one. They are two main individual hydrogeological units, developing high potential aquifers.

The alluvial deposits of the Western one (Fig. 2), which is the examined area of this study, constitute a system of unconfined shallow aquifers, extending in the upper layers, and successive confined—artesian aquifers developing in the dipper permeable layers (Marinos et al. 1995, 1997). This system besides the percolated surface water is also supplied by water through the lateral infiltration from the karstic aquifers of the alpine carbonate formations, outcropping in the margins of the basin. In general, the richest aquifers are developed in the Western sub-basin of Thessaly plain, due to their rich supply both from the big infiltrating part of the surface runoff and the lateral infiltration. The overexploitation of these aquifers during the last decades led to the manifestation of land subsidence phenomena (Marinos et al. 1995, 1997), with extended damages in some sites (Rozos et al. 2010).

According to geological studies of Western Thessaly basin (Mariolakos et al. 2001; Rozos and Tzitziras 2002), Mesozoic Alpine formations outcrop in the margins of the study area, while, post-Alpine deposits are presented in the lowland of the basin. The Mesozoic Alpine formations consist of Schist–chert formation, Ophiolites, Molassic formations, Limestones, and Flysch sediments (Fig. 2). They belong to the Pelagonian (Subpelagonian) geotectonic zone, and they constitute the bedrock of post-Alpine deposits of the West Thessaly basin. The post-Alpine formations, the younger of which are related with the subsidence phenomena, include:

- Neogene formations of fluvial and lacustrine origin consisting of red clayey silts and cohesiveness clayey sands. Scattered gravels and pebbles of various origin and



**Fig. 2** Generalized geological map of Western Thessaly basin. The *rectangle in the centre* shows the location of the study area (I.G.M.E 1969)

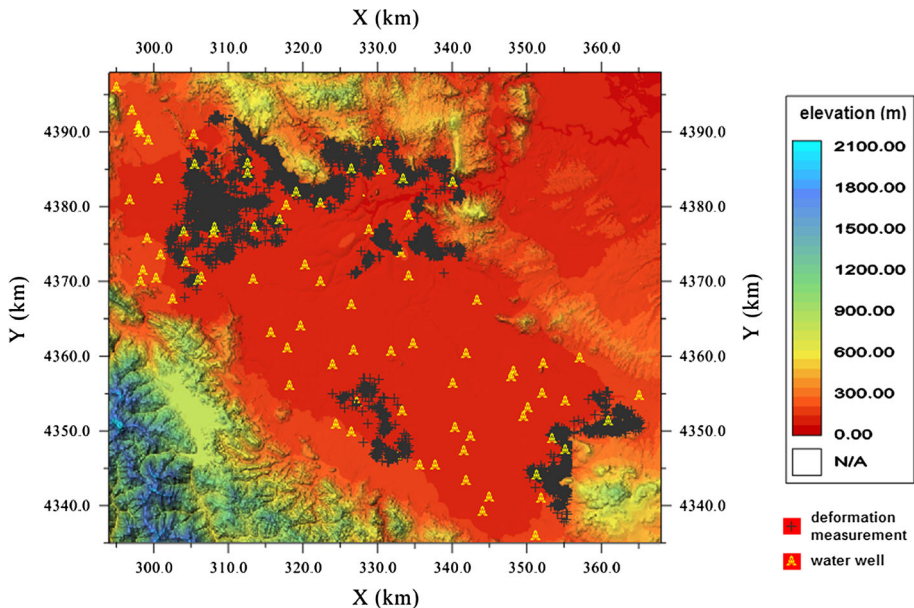
semicoherent conglomerates are also participating. The lacustrine deposits include friable gray to light gray marls, along with intercalations at places of sandstones and conglomerates (Mariolakos et al. 2001).

- Pleistocene sediments, terrestrial in origin including clayey silts, sandy silts, sandy clays, and sands, with grits and gravels. These sediments appear in extensive surface development at West Thessaly basin and gain considerable thicknesses even near its margins. Because of that lithology, high potential aquifers are developed, that undergo intensive exploitation (Rozos and Tzitziras 2002).

### 3 Dataset

Commonly used methods to measure land subsidence include conventional surveying, borehole extensometers, Global Positioning Systems (GPS), conventional InSAR Interferometric synthetic aperture radar (InSAR), and its recent development Persistent Scatterer Interferometry (PSI) (Galloway et al. 1999; Maliva and Missimer 2012). The methods vary in the resolution, cost, and practical spatial density of measurements. Borehole extensometers have the finest resolution and greatest accuracy, but are expensive to construct. As a result, there is typically a low spatial density of extensometers in most study areas. Ideally, multiple methods should be used in which, for example, extensometer data may serve as a control on less accurate methods with coarser resolutions. In any case, exclusive application of PSI technique in hydrogeological research and monitoring within the past decade has led to improved results (Ferretti et al. 2000, 2001).

Throughout of the Western Thessaly basin, several water wells were drilled (Fig. 3), in order to provide data for various hydrogeological studies (Kallergis 1973; Sogreah 1974).



**Fig. 3** Plot of water wells and PSI measurement points locations in the study area of Western Thessaly basin

PSI measurements are available from the European Space Agency (ESA), as shown in Fig. 3.

Our dataset includes two types of information: (a) Monthly piezometric time series taken from 82 water wells from 1974 to 2010 and (b) PSI deformation time series taken at 68767 points from 1992 to 2003. It is obvious that the distribution of water level and ground deformation measurements is not uniform in space and time. The PSI has been applied primarily in urban environments, where the density of stable scatterers typically is quite high (as many as a few hundred per square kilometer). Over natural terrain, which is our case as shown in Fig. 3, the scarcity of stable targets severely limits PSI's successful application and results in a strong differentiation in sampling density (Galloway and Burbey 2011).

Due to the gaps in the sampling grid as explained above, it is important in the next steps of our work to examine the use of one variable as auxiliary for the estimation of the other. A necessary condition for this is the existence of a certain degree of correlation between the two variables.

#### 4 Methods

The aim of the geostatistical analysis performed here is to estimate the best spatial distribution and temporal extension of ground deformations and water level in the West Thessaly basin. Geostatistical spatiotemporal models provide a probabilistic framework for data analysis and predictions that builds on the joint spatial and temporal dependence between observations.

Theoretically, stochastic models cannot explain by themselves causal effects stemming from the underlying physical processes. The physics of the phenomenon under study can be accounted for by deterministic models involving solution of the appropriate governing equations. In our case, where the modeling of piezometric head levels in an aquifer is intended, solution of the flow equation is required. Such deterministic models typically require a large number of input parameters that are difficult to determine due to limited or indirect sampling (Kyriakidis and Journel 1999). Stochastic models, on the other hand, are based typically on a small number of parameters and they aim at building a process that only follows a measured spatiotemporal variability, without obeying the underlying equations. Thus, they can be considered as alternative approaches where applicable.

Geostatistics provides tools for joint analysis of the space and time components and builds on the extension of established spatial techniques developed independently in mining (Matheron 1962; Journel and Huijbregts 1978), to include time as an additional space dimension. Such extension does not require regularity of sampling either in space or in time.

The problem of local estimation is to find the best estimate of the conditional mean of a random variable with respect to neighboring observations, over a limited domain the dimensions of which are small compared with the dimensions of the quasi-stationary (homogeneous) zones of the modeled area. The available information used for local estimation within quasi-stationary zone is generally made up of a set of data (e.g.,  $n$  core measurements) and structural information (e.g., the variogram model characterizing the special variability in the studied zone).

Ordinary kriging (Goovaerts 1997; Deutsch and Journel 1998) is a local estimation technique which provides the best linear unbiased estimator of the unknown characteristic studied. This limitation to the class of linear estimators is quite natural, since it means that

only the second-order moment of the random function (i.e., the covariance or variogram) is required, and in general, it is possible in practice to infer the moment.

Practically, in order to estimate the value of a variable  $Z_0$  in a point  $x_0$  of the space–time, using a set of values of the same parameter measured on  $n$  nearby points  $x_\alpha$  ( $\alpha = 1, n$ ), a linear combination of the measurements is formed:

$$Z_0^*(x_0) = \sum_{\alpha=1}^n \lambda_\alpha^0 Z_0(x_\alpha) \tag{1}$$

where the vector of the coefficients  $\{\lambda_\alpha^0\}$  is calculated so as to ensure an unbiased estimator and to minimize the variance of the difference between the potentially observable value and the estimated value at the estimation location. Minimization takes into account the spatial variability of the parameter expressed by the variogram function  $\gamma_0(h)$ , which is the semivariance of the variable increments with respect to distance  $h$ :

$$2\gamma_0(h) = \text{var}[Z_0(x+h) - Z_0(x)] \tag{2}$$

A variogram model is adjusted on the experimental variograms by means of a fitting operation. Ordinary kriging is characterized by a measure of its accuracy, which is the estimation error variance. This is useful in order to define estimation uncertainty and to outline areas that need a supplemental sampling.

Ordinary cokriging (Journel and Huijbregts 1978; Goovaerts 1997) is used when one variable does not have been sampled sufficiently to provide the estimates of acceptable precision. The precision of this estimation may then improve by considering the special correlations between this variable and other better sampled variables. From a theoretical point of view, cokriging is not different from kriging; difficulties arise essentially from notations, since an extra index (1) is required to differentiate between the variables.

In order to estimate the value of a variable  $Z_0$  in a point  $x_0$  of space–time by its samples at  $n_0$  nearby points  $x_{a_0}$  ( $\alpha = 1, n_0$ ), a set of  $p$  auxiliary variables  $Z_i$  is used to improve precision. These variables have to be spatially correlated to  $Z_0$  and must be sampled at  $\sum_{i=1}^p n_i$  points  $x_{a_i}$  in the vicinity of  $x_0$ .

Considering the resulting  $p + 1$  variables, the estimator is:

$$Z_0^*(x_0) = \sum_{i=0}^p \sum_{\alpha=1}^{n_i} \lambda_\alpha^i Z_i(x_{a_i}) \tag{3}$$

A minimization procedure similar to ordinary kriging is used to determine the matrix of coefficients  $\{\lambda_\alpha^i\}$ , which introduces spatial variability of all variables by means of the set of direct and cross-variograms  $\{\gamma_{ij}(h)\}$ . The generic cross-variogram between variables  $Z_i$  and  $Z_j$  is defined as the semicovariance of the pair increments:

$$2\gamma_{ij}(h) = \text{cov}[(Z_i(x+h) - Z_i(x)), (Z_j(x+h) - Z_j(x))] \tag{4}$$

The fitted variogram model must guarantee mathematical coherence. The most frequently used model is the linear model of coregionalization (Journel and Huijbregts 1978, Goovaerts 1997), according to which all the direct and cross-variograms are derived from linear combinations of  $n$  basic direct variograms  $\{\gamma_k(h), k = 1$  to  $n\}$ , i.e.,

$$\gamma_{ij}(h) = \sum_{k=1}^n b_{ij}^k \cdot \gamma_k(h) \quad \text{with} \quad b_{ij}^k = b_{ji}^k, \quad \forall k, \tag{5}$$

where,  $\forall k$  fixed, the coefficient matrix  $\{b_{ij}^k\}$  is positive definite. Model adjustment is realized by means of a fitting operation on the experimental variograms, respecting the condition that matrix  $\{b_{ij}^k\}$  must be positive definite.

## 5 Results and discussion

### 5.1 Correlation between deformations and water level fluctuation

A qualitative analysis to investigate the correlation of the spatial distribution, between the observed deformation pattern and a number of potential sources, like geological–hydro-geological and man-made parameters, was carried out in the area by Rozos and Tzitziras 2002.

We perform an initial quantitative examination of the correlation between the piezo-metric level and the deformation pattern in the PSI data, by linear regression at selected experimental locations (Table 1).

The results do not indicate a clear relation between the above variables. Fair correlation coefficients between the PSI dataset and the water level fluctuation have been observed, as for example, a value of  $-0.88$  in the Farsala area (Fig. 4a), while in some points poor correlation coefficients are found, as for example a  $-0.3$  in Farkadon area (Fig. 4b).

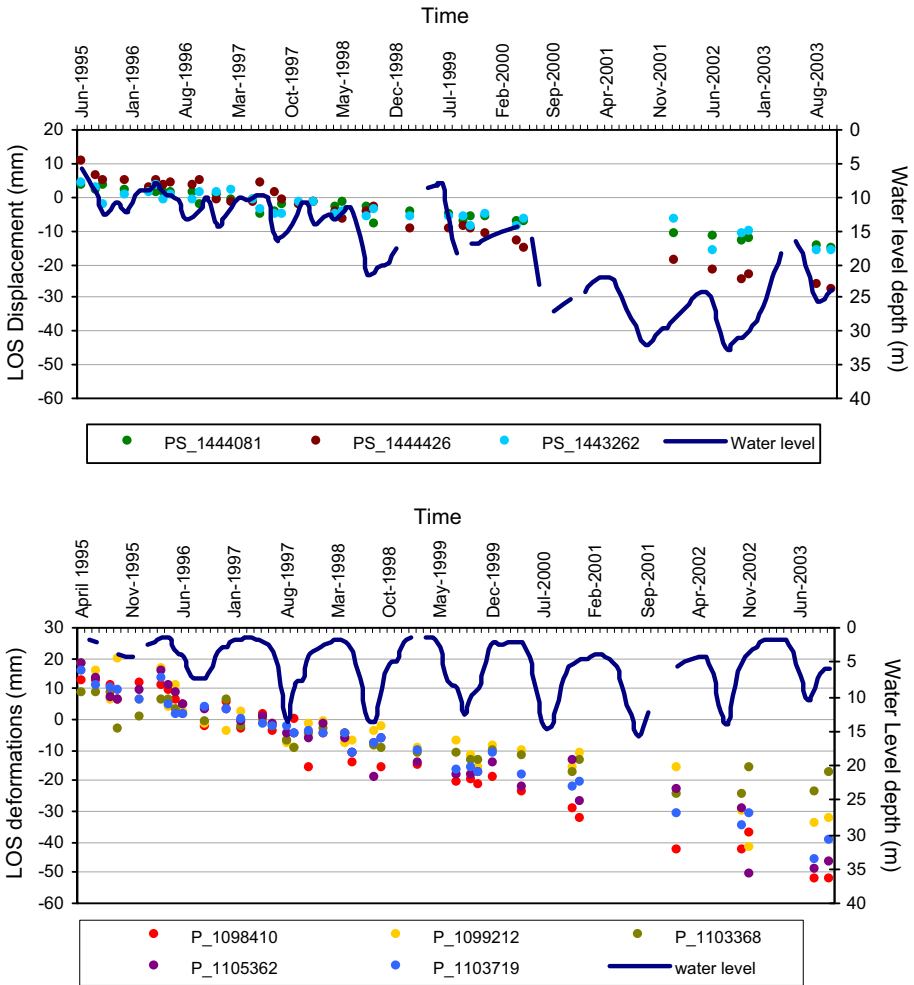
### 5.2 Structural analysis

Geostatistical spatiotemporal models consider a probabilistic nature of the underlined phenomenon and build on the joint spatial and temporal dependence between observations. Under the above statement, these techniques assume some spatiotemporal correlation of the natural phenomena governed by random processes. This correlation permits a certain degree of interdependence between the values of the attributes at different geographic and temporal scales.

**Table 1** Distance between water wells and PS locations

Borehole	PS_ID	Distance between borehole and PS location (m)
LB119	1444081	217
	1444426	309
	1443262	302
D27	1098410	897
	1099212	758
	1103368	408
	1105362	477
	1103719	858



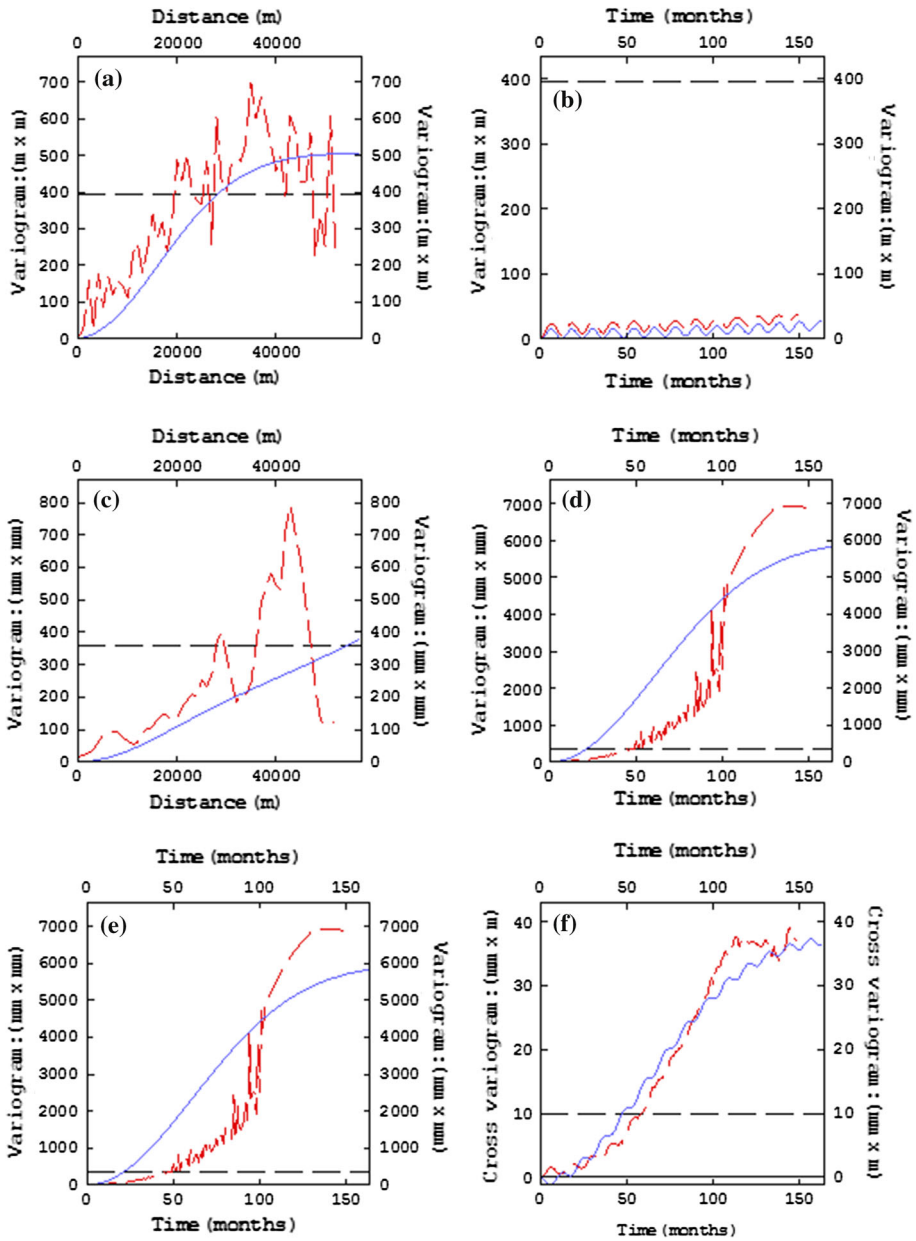


**Fig. 4** Persistent Scatterer (PS) time series and water level fluctuation in: **a** Farsala (Southeastern part of the basin)—water well LB119 and **b** Farkadon (Northeastern part of the basin)—water well D27

In order to investigate exhaustively the correlation between deformation and piezometric level measurements in the space and time, it is necessary to study the individual variograms and the cross-variogram of the above variables.

The experimental variograms of ground displacements and water level and also the cross-variograms between them were calculated in space and time with a lag size of 1 month on the temporal direction and 1,000 m in the spatial domain (Fig. 5). These variograms show an anisotropic variability, which is expected due to the differentiation between the spatial and temporal directions. The sills of the cross-variograms (Fig. 5) are indicative of the correlation between ground deformations and water level in space and time. The above result is in accordance with the theoretically expected: It is well known (Galloway and Burbey 2011) that there is a direct relation between water level decline and land subsidence.





**Fig. 5** Experimental and fitted spatiotemporal cross-variogram models for: **a** spatial variogram water level  $\times$  water level, **b** temporal variogram water level  $\times$  water level, **c** spatial variogram deformations  $\times$  deformations, **d** temporal variogram deformations  $\times$  deformations, **e** spatial cross-variogram water level  $\times$  deformations, **f** temporal cross-variogram water level  $\times$  deformations. *Thin dashed polylines* represent experimental variograms; *continuous lines* represent variogram components of the linear coregionalization model

**Table 2** Nested variogram components of the linear coregionalization model, showing the spatiotemporal dependencies between ground deformations (def) and water level (wl)

Model	Sill			Scale Factor (Practical Range)			Third Parameter
	wl–wl	wl–def	def–def	x	y	Temporal	
Gaussian	500	–50	150	40,000	40,000	1,800	
Gaussian	1.62	40	6,000	500,000	500,000	150	
CosExp	7.39	–0.68	1.45	9,000	9,000	9,000	12

The theoretical variogram fitted to the experimental data follows the linear coregionalization model, according to Eq. 5. Three nested structures, two gaussian and one exponential cosine (Chilès and Delfiner 2012), were linearly combined to express the spatiotemporal inter-dependencies of ground deformation and water level, individually and between them (Table 2). The first gaussian model was adjusted to reproduce mainly the spatial continuity of ground deformations and water level individually. This continuity extends isotropically up to 40,000 m. The second gaussian model affects mostly the temporal continuity of both variables, which extends practically up to 10 years. The exponential cosine model with period 12 simulates the yearly variation of water level due to seasonal fluctuation of rainfall.

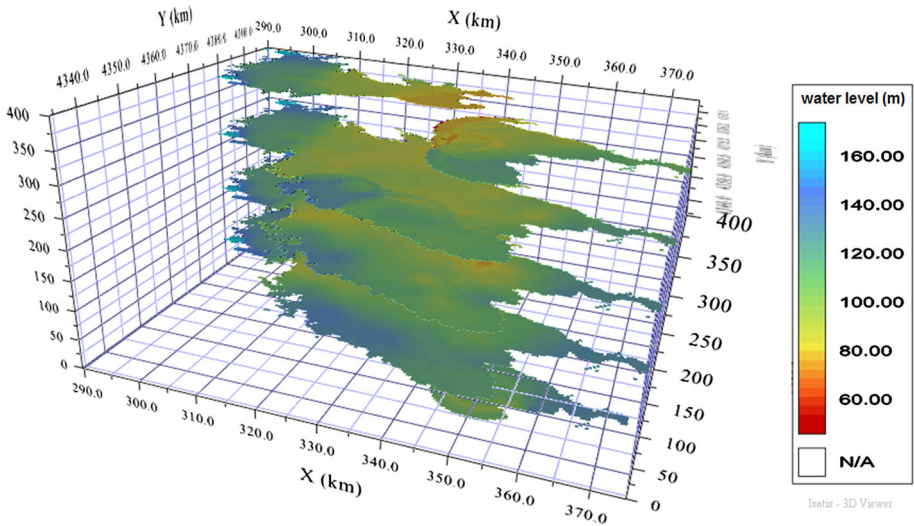
### 5.3 Spatiotemporal estimation

As described in Paragraph 3, ground deformation measurement points are not uniformly distributed in space and time, in contrast to water level measurement wells. Since the two variables of interest are correlated, as indicated by their cross-variogram, the application of cokriging is expected to be useful for the improvement of estimation. In this direction, we compared both kriging and cokriging for the estimation of ground deformations, with water level as an auxiliary variable. The numerical model was calculated in a spatiotemporal grid (Appiah et al. 2011), extending on 180 km × 140 km in space and 500 months in time (Fig. 6), divided to 12,600,000 elements of 500 m × 500 m × 1 month. The coordinates of the center of the lower left block are  $x = 290,000$  m,  $y = 4,330,000$  m, and  $z = 0$  which corresponds to December 1971. The application of cokriging algorithm was performed using ISATIS<sup>®</sup> software from Geovariances.

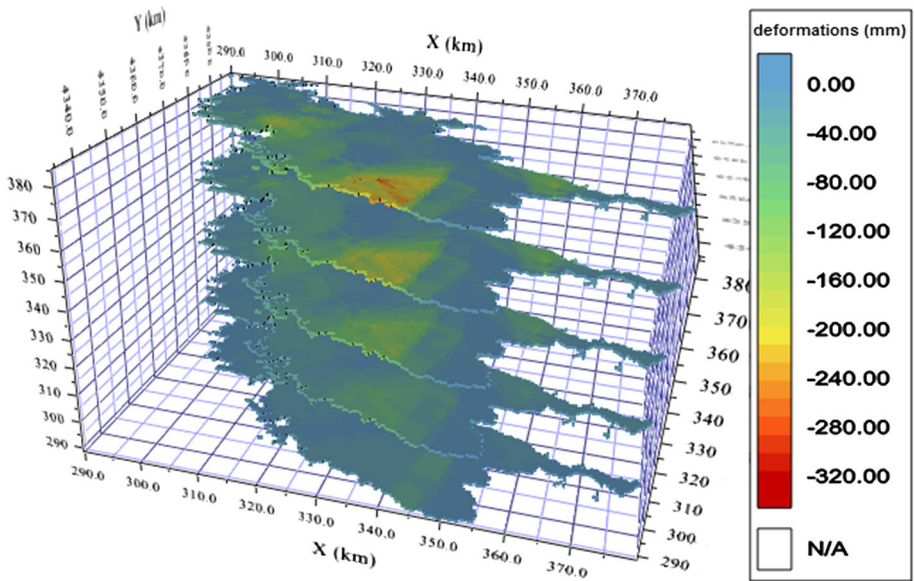
The interpolation results are shown in the 3D models of Figs. 6, 7 and 8. A continuous decline of water level and an increase in ground deformations in time are evident. The unwanted smoothing effect of kriging is also apparent when comparing Figs. 7 and 8. The regular water sampling grid assists in the production of more realistic results by application of cokriging. A cumulative representation of the modeling results is shown in Figs. 9 and 10, indicating a decline in water level in the SE and NW areas of the basin and increased deformations in similar areas. In general, the spatiotemporal correlation between the two variables is visible, as expected by their cross-variogram.

### 5.4 Discussion: model applications

Figures 11 and 12 show the estimation errors for water level and ground deformations, respectively, at an example cross-section of the spatiotemporal model. The benefits of using water level as an auxiliary variable in the estimation of ground deformations are



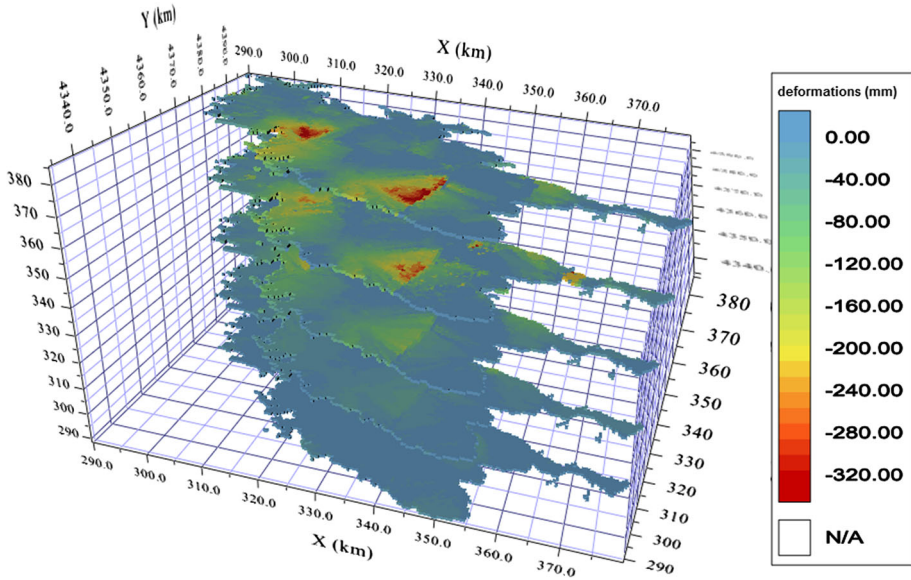
**Fig. 6** Results of spatiotemporal kriging estimation showing the evolution of water level in the study area of Western Thessaly basin. Z axis scale is in months. Time zero corresponds to December 1971



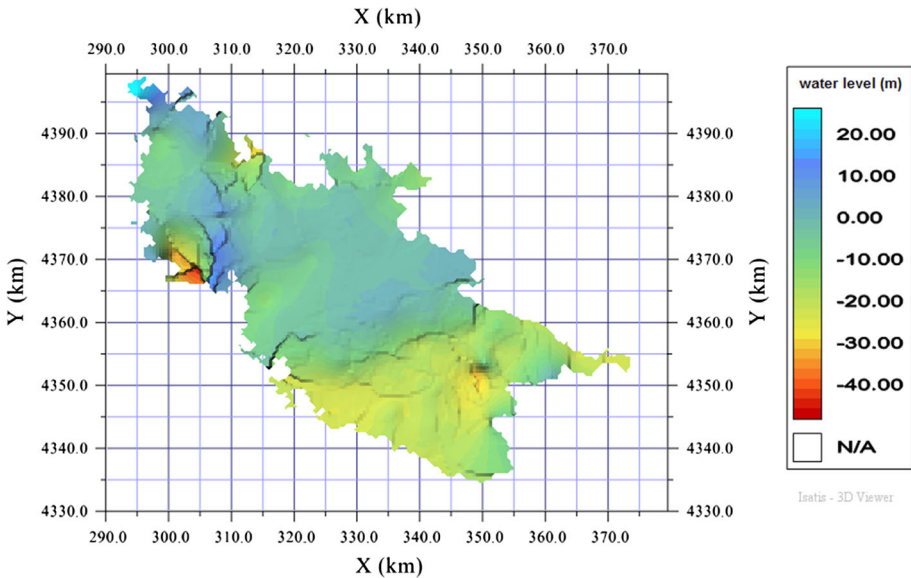
**Fig. 7** Results of spatiotemporal kriging estimation showing the evolution of deformations in the study area of Western Thessaly basin. Z axis scale is in months. Time zero corresponds to December 1971

evident in Fig. 12b, where the estimation errors are considerably lower compared to those in Fig. 12a, especially in the areas between the clusters of PSI measurements.

Concerning the applicability of our modeling methodology in water level, the variogram model indicates a practical spatial range of influence of approximately 40 km and also a periodically varying and continuously decreasing correlation in time (Fig. 5). The above

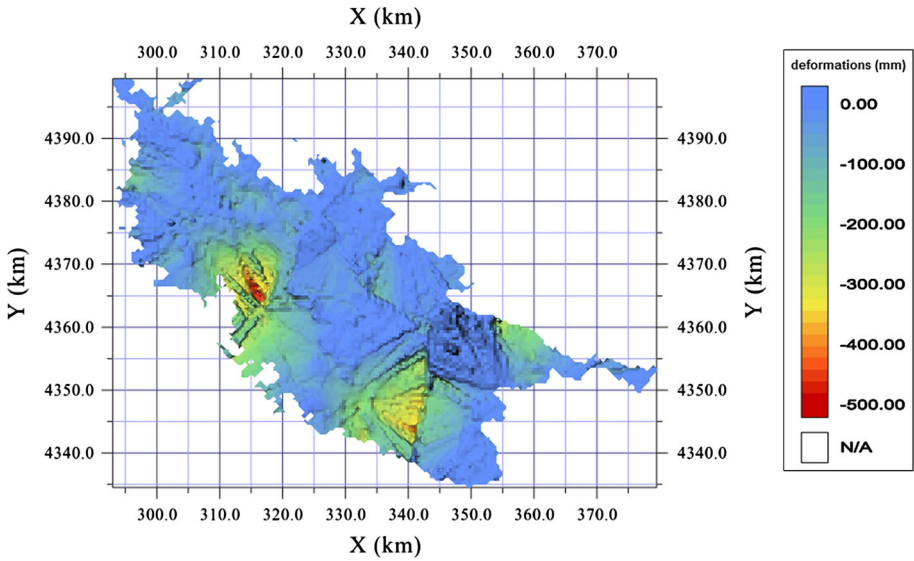


**Fig. 8** Results of spatiotemporal cokriging estimation showing the evolution of deformations in the study area of Western Thessaly basin, using water level as auxiliary variable. Z axis scale is in months. Time zero corresponds to December 1971

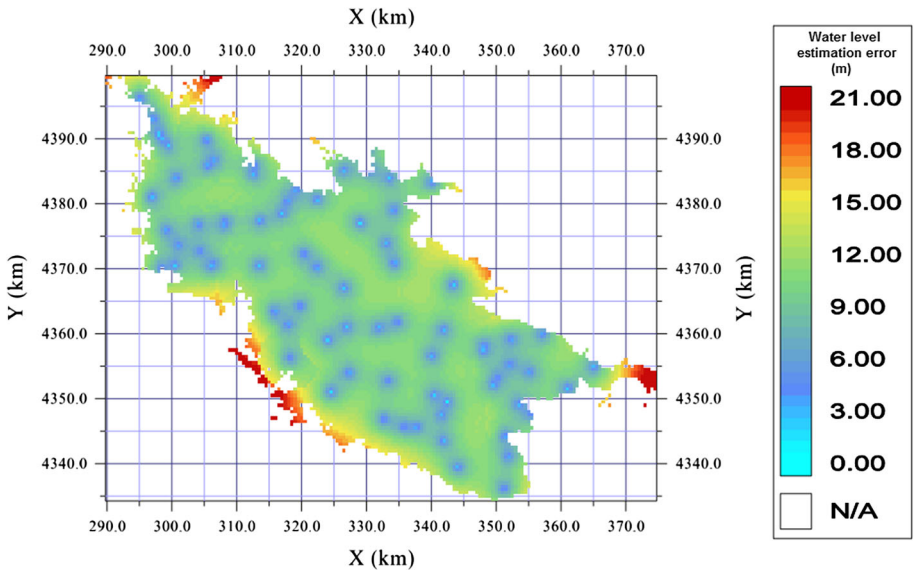


**Fig. 9** Cumulative estimated water level differences in the study area of Western Thessaly basin. Time interval: October 1974 up to October 1995. *Negative values* indicate water level decline

model parameters indicate that it is safe to interpolate within a spatial range of 40 km. It is also possible to predict future values of water level fluctuation. Beyond the above limits, errors may occur.



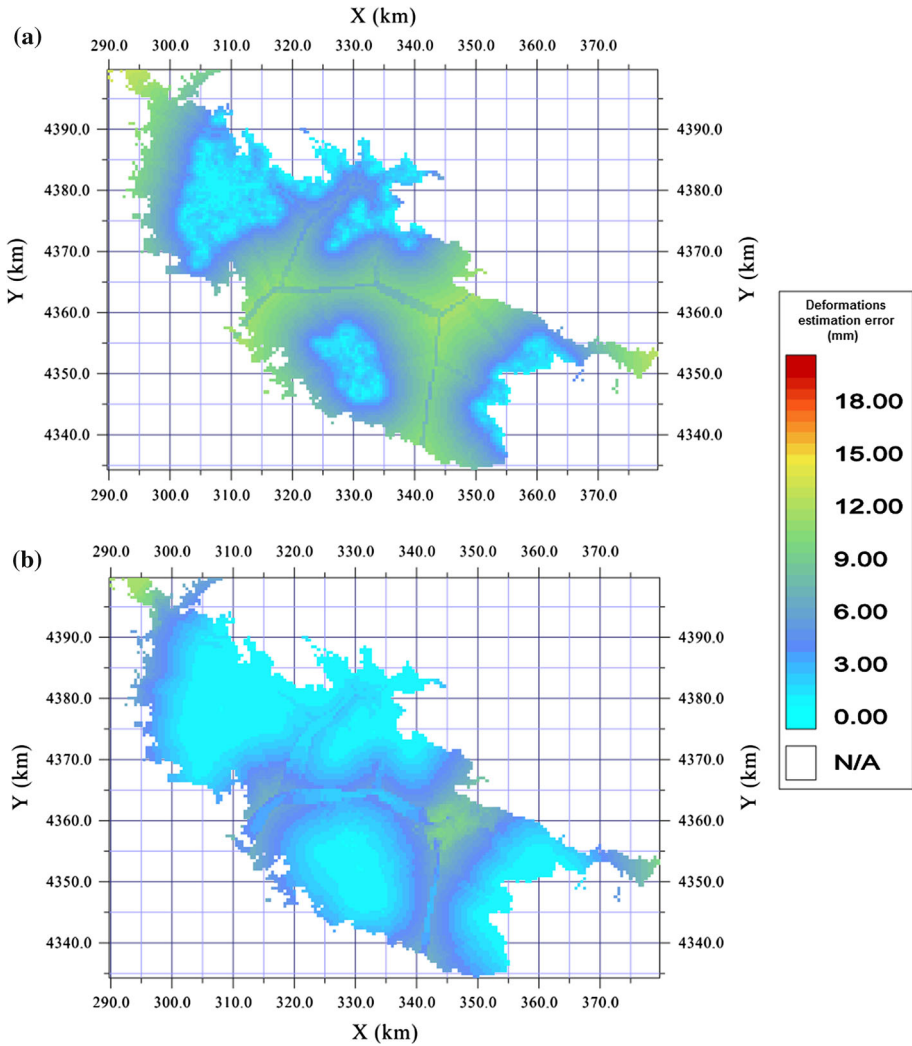
**Fig. 10** Cumulative estimated deformations field in the study area of Western Thessaly basin. Time interval: March 1995 up to November 2003



**Fig. 11** Water level estimation error in October 1995 in the study area of Western Thessaly basin

Concerning ground deformations, the variogram model indicates a spatial range of influence of 40 km and also a temporal range of influence of 10 years (Fig. 5). The above parameters describe a range of safe interpolation approximately at 40 km. It is also





**Fig. 12** Deformations estimation error in October 1995 in the study area of Western Thessaly basin: **a** kriging and **b** cokriging with water level

possible to predict future values of ground deformations up to 10 years. Exceeding the above limits may lead to errors.

## 6 Conclusions and future research

Study of the variograms of piezometric level and ground deformations in the Western Thessaly basin has shown that it is possible to perform spatiotemporal estimation of these variables, using geostatistics. The cross-variogram model indicates that these variables are spatiotemporally correlated. The use of the uniformly sampled water level as an auxiliary

variable for the estimation of ground deformations produces more realistic results, by considerably reducing the estimation error.

Model parameters indicate that it is safe to interpolate piezometric level within a spatial range of 40 km. It is also possible to predict future values of water level fluctuation. Concerning ground deformations, the variogram model indicates a range of safe interpolation approximately at 40 km. Prediction of future values of ground deformations is also allowable up to 10 years.

In order to decrease the estimation errors when forecasting distant values of the model, additional use of other parameters such as soil quality, hydraulic conductivities, or various boundary conditions might be of use. A further future step of the research will be to take into account the above parameters via the incorporation of deterministic laws of ground water flow to our stochastic model.

**Acknowledgments** The Terrafirma Extension project (<http://www.terrafirma.eu.com/index.htm>) has funded the SAR imagery processing. The project is one of the many services supported by the Global Monitoring for Environment and Security (GMES) Service Element Programme, promoted and financed by ESA. The project is aimed at providing civil protection agencies, local authorities, and disaster management organisms with support in the process of risk assessment and mitigation by using the PSI. The authors gratefully acknowledge the German Aerospace Centre (DLR) for having processed the SAR data. The authors also acknowledge the Institute of Geology and Mineral Exploration of Greece (IGME) and the Thessaly Prefecture for the supply of all necessary borehole data for the analysis. Finally, the authors thank the two anonymous reviewers who made critical reviews and detailed comments and gave the opportunity to substantially improve the original manuscript.

## References

- Andronopoulos V, Rozos D, Hatzinakos I (1991) Subsidence Phenomena in the Industrial Area of Thessaloniki–Greece. In: 4th International Symposium on Land Subsidence, IAHS, UNESCO, May 12–17, 1991, Houston, Texas, USA
- Apostolidis E, Georgiou H (2007) Geotechnical research of the surface ground ruptures in Thessaly basin sites, recording and documentation. Institute of Geology and Mineral Exploration (IGME), unpublished report (in Greek)
- Appiah SK, Mueller U, Cross J (2011) Spatio-temporal modelling of malaria incidence for evaluation of public health policy interventions in Ghana, West Africa. In: 19th International Congress on Modelling and Simulation, Perth, Australia
- Armstrong M, Chetboun G, Hubert P (1993) Kriging the rainfall in Lesotho. In: Soares A (ed) *Geostatistics Troia'92*, vol 2. Kluwer, Dordrecht, pp 661–672
- Bogaert P, Christakos G (1997) Spatiotemporal analysis and processing of thermometric data over Belgium. *J Geophys Res* 102(D22):25831–25846
- Bras RL, Rodrigues-Iturbe I (1984) *Random functions and hydrology*. Addison-Wesley, Reading 559 p
- Chilès JP, Delfiner P (2012) *Geostatistics: modeling spatial uncertainty*, 2nd edn. Wiley, New York
- Deutsch CV, Journel AG (1998) *Geostatistical software library and user's guide*. Oxford University Press, Oxford
- Ferretti A, Prati C, Rocca F (2000) Nonlinear subsidence rate estimation using permanent scatterers in differential SAR interferometry. *IEEE Trans Geosci Remote Sens* 38:2202–2212
- Ferretti A, Prati C, Rocca F (2001) Permanent scatterers in SAR interferometry. *IEEE Trans Geosci Remote Sens* 39(1):8–20
- Galloway D, Burbey T (2011) Review: regional land subsidence accompanying groundwater extraction. *Hydrogeol J* 19:1459–1486
- Galloway D, Ingebritsen SE, Riley FS, Ikehara ME, Carpenter MC (1999) Land subsidence in the United States. In: Galloway D, Jones DR, Ingebritsen SE (eds) *Land subsidence in the United States: U.S. Geological Survey Circular*, vol 1182. U.S. Geological Survey, Reston, Virginia, pp 141–158
- Goovaerts P (1997) *Geostatistics for natural resources evaluation*. Oxford University Press, Oxford



- Goovaerts P, Sonnet P (1993) Study of spatial and temporal variations of hydrogeochemical variables using factorial kriging analysis. In: Soares A (ed) *Geostatistics Tróia'92*, vol 2. Kluwer, Dordrecht, pp 745–756
- Handcock MS, Wallis JR (1994) An approach to statistical spatial-temporal modeling of meteorological fields (with discussion). *J Am Stat Assoc* 89(426):368–390
- Haslett J, Raftery AE (1989) Space–time modeling with long-memory dependence: assessing Ireland's wind power resource (with discussion). *Appl Stat* 38(1):1–50
- Heuvelink GBM, Musters P, Pebesma EJ (1997) Spatio-temporal kriging of soil water content. In: Baaffi E, Schofield N (eds) *Geostatistics Wollongong'96*, vol 2. Kluwer, Dordrecht, pp 1020–1030
- IGME (1969) Geological map of Greece, Farsala Sheet (scale 1:50,000). IGME Publications, Athens
- Journel AG, Huijbregts ChJ (1978) Mining geostatistics. Academic Press, London, p 600
- Kallergis G (1971) Ground subsidences during the drawdown of artesian aquifers due to their limited elasticity (in Greek). *Technika Chronika* magazine, Athens, pp 599–602
- Kallergis G (1973) Hydrogeological study in sub-basin of Kalampaka (Western Thessaly). Institute of Geology and Mineral Exploration (IGME), unpublished report, vol 14, No 1, Athens (in Greek)
- Kyriakidis PC, Journel AG (1999) Geostatistical space–time methods: a review. *Math Geol* 31:651–684
- Maliva R, Missimer T (2012) *Arid lands water evaluation and management*. Springer, Berlin
- Marinos P, Thanos M, Perleros V, Kavadas M (1995) Water dynamic of Thessaly basin and the consequences from its overexploitation. In: *Proceedings of the 3rd Hydrogeological Congress* (in Greek), Heraklion Crete
- Marinos P, Perleros V, Kavadas M (1997) Deposited and karsic aquifers of Thessaly plain. New data for the status of their overexploitation. In: *Proceedings of the 4th Hydrogeological Congress* (in Greek), Athens
- Mariolakos H, Lekkas S, Papadopoulos T, Alexopoulos A, Spyridonos E, Mandekas I, Andreadakis E (2001) Underground tectonic structure in Farsala plain (Thessaly) as a determinative factor of the formation of the hydrogeological conditions of the area. In: *Proceedings of the 9th Congress of Greek Geological Society* (in Greek)
- Matheron G (1962) *Traite de geostatistique appliquee*, Tome I: *Memoires du Bureau de Recherches Geologiques et Minieres*. Editions Technip, Paris
- Papritz A, Fluhler H (1994) Temporal change of spatially autocorrelated soil properties: optimal estimation by cokriging. *Geoderma* 62:29–43
- Rouhani S, Wackernagel H (1990) Multivariate geostatistical approach to space–time data analysis. *Water Resour Res* 26(4):585–591
- Rozos D, Tzitziras A (2002) Report of the Engineering geological examination of ground water in Farsala area. Institute of Geology and Mineral Exploration (IGME), unpublished report (in Greek)
- Rozos D, Sideri D, Loupasakis C, Aposolidis E (2010) Land subsidence due to excessive ground water withdrawal. A Case Study from Stavros—Farsala Site, West Thessaly Greece. In: *Proceedings of the 12th International Congress*, Patras, Greece
- Seguret S, Huchon P (1990) Trigonometric kriging: a new method for removing the diurnal variation from geomagnetic data. *J Geophys Res* 95(B13):21383–21397
- Sogreah SA (1974) Groundwater development project of the plain of Thessaly. Republic of Greece, Ministry of Agriculture, Directorate General of Agricultural Development and Research Land Reclamation Service, Athens
- Soulios G (1980) Subsidence of recent deposits due to pumping of underneath aquifers. An example from Greek territory. *Technika Chronika Magazine*, Athens
- Soulios G (1997) Subsidence de terrains alluviaux dans le sud-est de la plaine de Thessalie, Grèce. In: *Proceedings International Symposium on Engineering Geology and the Environment*. Balkema, Rotterdam