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Time-dependent methods to evaluate the effects of urban sprawl on groundwater quality: a synthesis

Metodi tempo-dipendenti per valutare gli effetti dello urban sprawl sulla qualità delle acque sotterranee: sintesi

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Riassunto: Le risorse idriche mondiali sono soggette ad un futuro difficilmente prevedibile a causa dell'instabilità nelle dinamiche del ciclo dell'acqua e della crescente richiesta legata alla popolazione in aumento e allo sviluppo economico. Perciò sono necessarie azioni, strategie e soluzioni pratiche per garantire una sicura, accessibile, conveniente ed adeguata fornitura di acqua potabile, sia nel breve che nel lungo termine, per rispondere alle necessità degli ecosistemi e di una popolazione in crescita.

A partire dagli anni '50, l'Europa sta vivendo il fenomeno dello urban sprawl, caratterizzato da un'urbanizzazione non organizzata e non più correlata alla crescita della popolazione (EEA 2006). Gli impatti dello urban sprawl minacciano sia le aree rurali che naturali e la qualità della vita delle persone residenti nelle città, con effetti negativi sulla qualità dell'aria e sulla qualità e quantità delle acque superficiali e sotterranee.

Le Direttive europee sulla protezione delle acque sotterranee (Water Framework Directive, 2000/60/EC; Groundwater Directive, 2006/118/EC) richiedono agli stati membri di raggiungere uno status chimico accettabile dei propri corpi idrici sotterranei e di identificare le aree dove le acque sotterranee sono soggette a concentrazioni crescenti dei contaminanti. Per soddisfare le richieste dell'Unione Europea è stata sviluppata una metodologia tempo-dipendente per la valutazione della vulnerabilità degli acquiferi, che tenesse in considerazione sia lo stato attuale che l'evoluzione della contaminazione delle acque sotterranee nell'area lombarda della Pianura Padana. Tale approccio si avvale dei vantaggi di un metodo statistico di tipo bayesiano per la valutazione della vulnerabilità degli acquiferi e di dati satellitari da scatterometro per delineare le aree urbane e monitorare la loro evoluzione. La metodologia proposta può determinare i potenziali impatti sulla qualità delle acque sotterranee nel caso in cui le politiche siano mantenute allo stato attuale oppure nell'ipotesi in cui saranno implementati nuovi interventi per la salvaguardia della risorsa idrica sotterranea.

Keywords: *groundwater vulnerability, statistical method, land use management, remote sensing, Po Plain.*

Parole chiave: vulnerabilità degli acquiferi, metodo statistico, gestione di uso del suolo, remote sensing, Pianura Padana.

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Abstract: *Freshwater resources are threatened worldwide with unknown and unpredictable fate, due to non-stationarity and change of water cycle dynamics, and increasing demand resulting from population growth and economic expansion. Thus, practical actions, strategies and solutions are necessary to ensure the short-term and long-term provision of adequate, affordable, accessible and safe freshwater supply to meet the needs of the growing human population and ecosystems.*

Since the mid-1950s, Europe is experiencing the phenomenon of urban sprawl, characterized by an unplanned incremental urban development, no more tied with population growth (EEA 2006). Impacts of urban sprawl threaten both the natural and rural environments and the quality of life for people living in cities, with worsening of air quality, and surface- and groundwater quality and quantity.

For the protection of groundwater, the European Union issued a series of Directives (Water Framework Directive, 2000/60/EC; Groundwater Directive, 2006/118/EC) that require member states to achieve a good chemical status of their groundwater bodies and the identification of areas where groundwater suffers increasing trends in contaminant concentrations. In order to cope with EU Directives, a time-dependent approach for groundwater vulnerability assessment is developed to account for both the recent status of groundwater contamination and its evolution in the Po Plain area of Lombardy Region (northern Italy). Such approach takes the advantages of a Bayesian spatial statistical method to assess groundwater vulnerability and satellite scatterometer data to delineate urban areas and monitor their evolution. The proposed approach can determine potential impacts of contamination events on groundwater quality, if policies are maintained at the status quo or if new measures are implemented for safeguarding groundwater resources.

Introduction

Urban sprawl is perceived as a specific physical formation of urban growth characterized by an excessive increase in urban land uses, decreasing urban densities, and a spatially dispersed distribution of households and economic functions (Siedentop and Fina 2012). Classically, it is a US phenomenon associated with the rapid low-densities outward expansion of US cities, in the early part of the 20th century, favored by the rapid growth of private car ownership. In Europe, cities have traditionally been much more compact, developing a dense historical core shaped before the emergence of modern transport system. However, since the 1950s, urban sprawl has become a common phenomenon even in Europe, with no apparent slowing in these trends (EEA 2006). The major impacts of urban sprawl in Europe are evident in increased energy, land and soil consumption, which threaten the regional environment, the social structure and the economy (EEA 2006). The main impacts on groundwater are: (a) the increase of non-point sources of contamination related to urban activities; (b) the reduction of the capacity of soil to act as a filter for contamination sources; (c) the decrease of permeable superficial surfaces, which influence the quantity of groundwater recharge; (d) the alteration of surface- and groundwater interactions.

For the protection of groundwater quality in the European Union, the Water Framework Directive (WDF, 2000/60/EC) and the Groundwater Directive (GWD, 2006/118/EC) require member states to achieve a good chemical status of their groundwater bodies. The GWD requires also the identification of areas where groundwater suffers increasing trends in contaminant concentration. Such activities would allow not only identifying already highly contaminated areas where expensive remediation measures need to be implemented, but also detecting areas where pro-active interventions need to be planned.

The objective of this study is to develop a time-dependent approach for groundwater vulnerability assessment to account for the recent status and the evolution of groundwater contamination, as required by the European Union. Specifically, the study focuses on the status of nitrate contamination in 2011 and its evolution from 2000 to 2011. The approach combines natural and anthropogenic factors to identify areas with a critical combination of high levels and increasing trends of nitrate concentrations, together with a quantitative evaluation of how different future scenarios would affect the quality of groundwater resources in a given area. The future scenarios will be referenced to 2020, and consider changes in anthropogenic sources of nitrate and natural factors estimated for the period 2011 to 2020. The time-dependent approach is illustrated for the Po Plain area in the Lombardy Region (northern Italy).

Method

Time-dependent approach

The proposed time-dependent approach to assess groundwater vulnerability is shown in Fig. 1. Each model shown in Fig. 1 has been developed using a Bayesian spatial statistical method (Weights of Evidence, Bonham-Carter 1994). Both natural and anthropogenic factors are taken into account as influencing groundwater vulnerability to nitrate contamination. Natural factors include geological and hydrogeological characteristics of the study area. Anthropogenic factors represents potential sources of nitrate contamination. According to the objective of each model, each factor is considered as static (i.e., it does not change in time) or dynamic (i.e., it changes in time).

The *spatial model* considers the status of nitrate contamination and nitrate sources at a generic time t_1. The *temporal model* takes into account the evolution of nitrate contamination and nitrate sources in the period between time t_0 and t_1. The *spatio-temporal model* considers both the status and the evolution of nitrate contamination and nitrate sources at a generic time t1 and between time t_0 and t_1.

Lastly, the approach allows considering possible evolutions of nitrate contamination, nitrate sources of contamination and natural factors in the future, developing a *predictive spatio-temporal model*, which refers to a hypothetical condition at time t_2, under the hypothesis of a given evolution between time t_1 and t_2. The *model of severity* is created comparing the status of vulnerable areas at time t_1 and at time t_2. The *model of severity* is obtained, firstly, comparing the *predictive spatio-temporal model* (at time t_2) with the *spatio-temporal model* (at time t_1) to evaluate the differences in terms of vulnerability between the two times and, secondarily, the comparison map is combined with the *spatial model* (at time t_1) to obtain the *model of severity*, as thoroughly described in Stevenazzi et al. (2017a).

The aim is identifying the critical areas where the combination of natural and anthropogenic factors could involve either the occurrence of nitrate contamination or their increasing trend in groundwater in the future, considering the vulnerable areas in the present.

The time-dependent approach is illustrated for the first two decades of the 2000s (Stevenazzi et al. 2015; Stevenazzi et al. 2017a). Spatial, temporal and spatio-temporal models refer to the status of nitrate contamination and nitrate sources in 2011 (t_1) and their evolution from 2000 (t_0) to 2011 (t_1). The predictive spatio-temporal model considers a hypothetical scenario of groundwater nitrate contamination in 2020 (t_2) and its variation during the period 2011–2020 (t_1–t_2), together with a hypothetical evolution of anthropogenic and natural factors in the same period.

Weights of Evidence technique

Among the various statistical methods, the Weights of Evidence (WofE, Bonham-Carter 1994) modelling technique has been chosen for its reliability in performing meaningful and scientific defensible groundwater vulnerability maps, which has been proved by various Authors (e.g., Arthur et al. 2007; Nolan et al. 2002). WofE is a cell-based modeling technique, which combines different spatial datasets in a Geographical Information System (GIS) environment to analyze and describe their interactions and generate

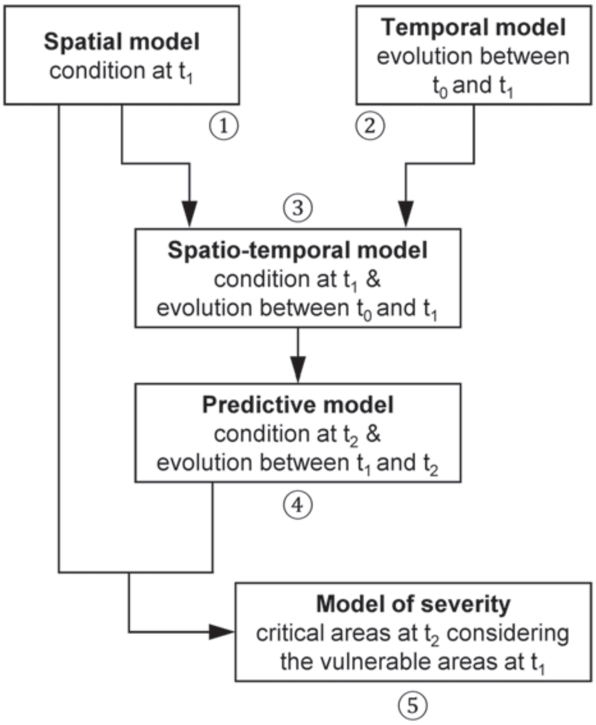

Fig. 1 - Flowchart of the time-dependent approach.

Fig. 1 - Schema di flusso dell'approccio "tempo-dipendente".

predictive patterns (Bonham-Carter 1994; Raines et al. 2000). WofE can be defined as a data-driven Bayesian method in a log-linear form that uses known occurrences (i.e., distribution of nitrate contamination). These data are used to obtain predictive probability maps from multiple weighted evidences (explanatory variables), which determine the spatial distribution of the occurrences in the study area (Raines 1999). Please refer to Arthur et al. (2007), Sorichetta et al. (2012) and Stevenazzi et al. (2017b) for a detailed description of how WofE can be used for assessing groundwater vulnerability. We remark here two main concepts of the WofE technique:

- For the purpose of the study, each spatial dataset must be significant from a statistical and a physical point of view. The first requirement means that the classes obtained from the generalization process (Sorichetta et al. 2012) respect the established level of significance (90 %). The second one means that the relationship between know occurrences and explanatory variables, obtained through the generalization process, is justifiable from a hydrogeological point of view;
- The final products of the WofE technique are predictive probability maps, representing groundwater vulnerability to a specific contaminant in the study area. The degree of vulnerability increases as probability increases: low probability values correspond to low vulnerability, whereas high probability values correspond to high vulnerability.

The study has been performed using the Spatial Data Modeler (Sawatzky et al. 2009) for ArcGIS 9.3 (ESRI 2008).

Study area

The study area is located within the Po Plain sector of Lombardy Region, in northern Italy (Fig. 2), and covers an area of about 13,400 km². The Po Plain is one of the most populated regions in Europe with a "sprawl without growth" pattern (Siedentop and Fina 2012), resulting from an initial phase of urban expansion from the 1950s to the 1970s, followed by an urban sprawl in the subsequent decades. This pattern qualifies the Po Plain as a representative pilot area to identify the interplay of urbanization and environmental, social and economic impacts after the rapid urban increase.

Fig. 2 - Location of the study area.

Fig. 2 - Ubicazione dell'area di studio.

Several advantages qualify such study area as an appropriate pilot area also for the application of the time-dependent approach:

- The geological and hydrogeological structure of the subsoil is well known (e.g., Regione Lombardia and ENI 2002): the plain subsoil is characterized by Plio-Pleistocene sediments, whose upper unit forms the shallow, unconfined aquifers mainly constituted by gravels and sands; the groundwater flow is generally oriented north-south toward the base level defined by the Po River, with a deviation to east-south-east in south-eastern Lombardy; the groundwater depth decreases from north to south, ranging from values higher than 70 m to less than 2 m.
- Groundwater quality is monitored by the Regional Environmental Agency (ARPA Lombardia 2017) since the beginning of the 2000s, through a network of about 500 wells covering the entire area with a nearly uniform spatial distribution.
- The distribution and evolution of factors influencing the deterioration of groundwater quality is available (i.e., urban and agricultural sources). This includes the availability of an innovative dataset to delineate urban areas with satellite scatterometer data. Radar backscatter data acquired by the SeaWinds scatterometer aboard the QuikSCAT satellite, together with the Dense Sampling

Method (QSCAT-DSM; Nghiem et al. 2009), have been used to identify and map urban extent and surface features at a posting scale of about 1 km² (Fig. 3, left column). Such satellite dataset has been collected in the decade of the 2000's, allowing to calculate the rate of urban change in this period in every cell across the world.

Among the various contaminants, the most common non-point-source contaminant found in groundwater of the Po Plain is nitrate (NO_3^-, Fig. 3, right column). Due to its high mobility and widespread presence in shallow groundwater, nitrate can be considered an ideal candidate to be used as environmental indicator of groundwater vulnerability to contamination (e.g., Tesoriero and Voss 1997). As demonstrated by various studies, nitrate contamination in the study area is related to agricultural and livestock activities (Masetti et al. 2008), as well as to urban areas (Crosta et al. 2015, Sorichetta et al. 2011).

The shallow, unconfined aquifer is the portion of aquifer on which this study focuses. From the monitoring well network, only those wells monitoring the shallow aquifer and having a minimum of eight measurements (Grath et al. 2001), in the period 2000-2011 (ARPA Lombardia, unpublished data, 2012), have been used in the analysis.

From Figure 3, it is interesting to note both the distribution of urban areas from scatterometer data (QSCAT-DSM, Fig. 3a, c) and nitrate concentration in groundwater (Fig. 3b, d) and their evolution from 2000 to 2010. An extended urban area is present in the northern sector of the plain, where residential

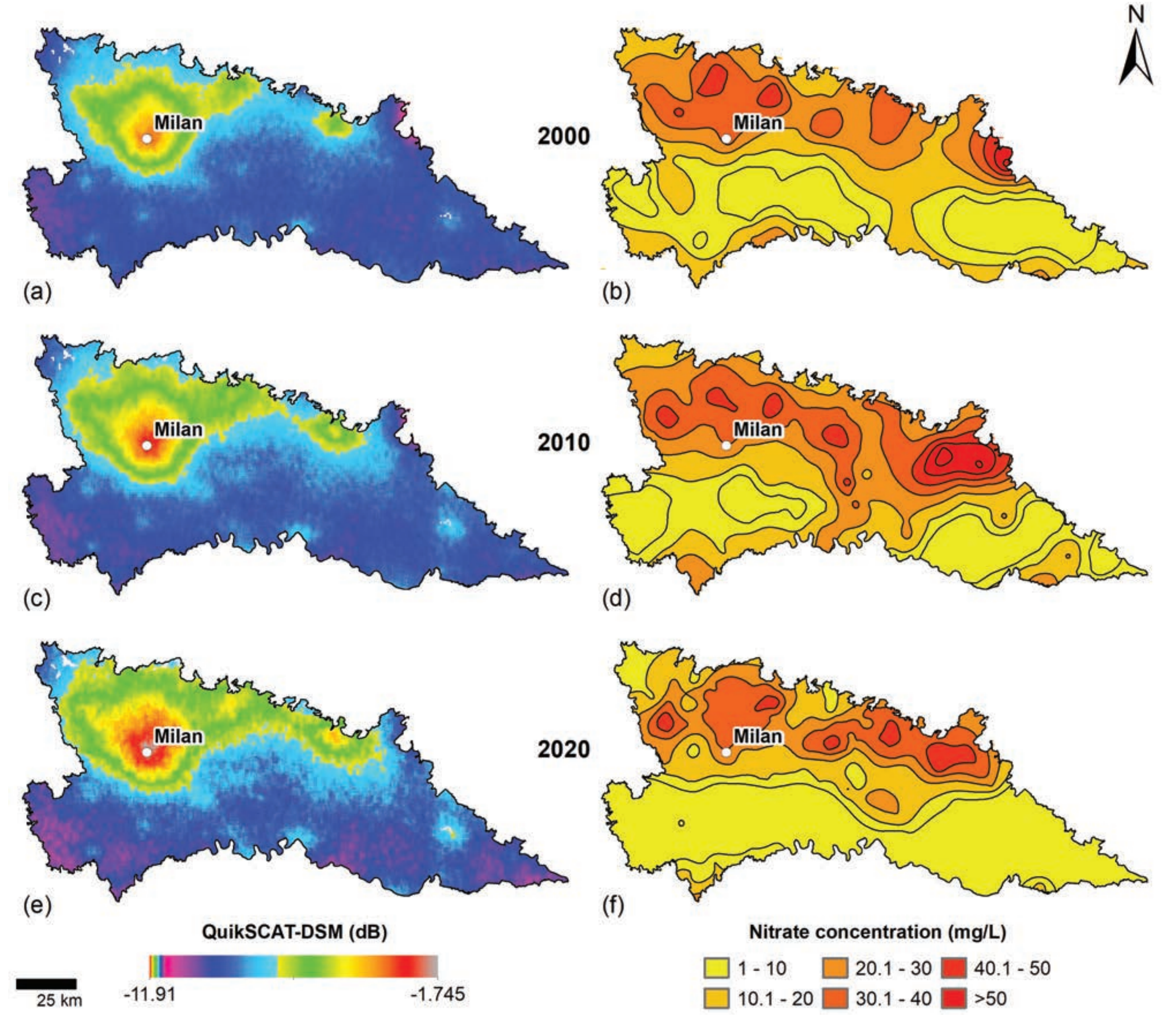

Fig. 3 - Evolution of urban areas and groundwater nitrate contamination in the Lombardy Plain area. QuikSCAT-DSM data acquired in 2000 (a), in 2010 (c) and projected in 2020 (e). Violet-to-blue colors represent rural areas. Yellow-to-red colors represent urban areas. Groundwater nitrate contamination measured in 2000 (b), in 2010 (d) and projected in 2020 (f).

Fig. 3 - Evoluzione delle aree urbane e della contaminazione da nitrati nelle acque sotterrane nella Pianura Lombarda. Dati QuikSCAT-DSM acquisiti nel 2000 (a), nel 2010 (c) e proiettati nel 2020 (e). I colori dal viola al blu rappresentano aree rurali. I colori dal giallo al rosso rappresentano aree urbane. Contaminazione da nitrati nelle acque sotterranee misurata nel 2000 (b), nel 2010 (d) e proiettata nel 2020 (f).

buildings and industries are located. Extended agricultural fields, scattered towns and few main cities characterize the southern sector of the plain. It can be noticed that urban areas have expanded from 2000 to 2010 especially around the city of Milan and along the main roads and highways (Fig. 3a, c). Similarly, high nitrate concentrations are mainly located in the northern sector of the plain. A deterioration of groundwater quality has occurred from 2000 to 2010, which is emphasized by the expansion of areas characterized by high nitrate concentrations in the northern and central sectors of the plain (Fig. 3 b, d).

By way of example, both QSCAT-DSM data and nitrate concentrations have been projected to 2020 (Fig. 3e, f), assuming that their changes in period 2011–2020 follow the same evolution from 2000 to 2010. In the assumption of the maintenance of the same conditions, it would be possible to assist to a continuous expansion of urban areas in the northern sector, with a great urban development in and around the City of Milan (Fig. 3e). On the opposite side, an improvement of groundwater quality could occur, with a considerable reduction of areas characterized by high nitrate concentrations limited in the northern sector of the plain (Fig. 3f).

Conceptual hydrogeological model

In the conceptual hydrogeological model, six explanatory variables are considered as factors influencing groundwater vulnerability to nitrate contamination in the study area. These variables were selected to capture the pathway and the main regional-scale processes that characterize the nitrate contamination pattern in groundwater:

- urban and agricultural sources, as distinct variables, representing the potential release of nitrates from the surface: a) QSCAT-DSM data and population density for each administrative unit are used as proxies representing urban nitrate sources; b) Nitrogen fertilizer loading at a municipal level is used to represent agricultural nitrate sources;
- soil protective capacity, representing the eventual degradation of nitrates through superficial soils;
- hydraulic conductivity of the vadose zone and groundwater depth, controlling the vertical spreading of contaminants in the unsaturated zone;
- groundwater velocity, representing the transport and dilution processes in the aquifer.

The importance of each variable in influencing groundwater vulnerability can differ according to its local spatial relation with the other variables.

The predictive scenarios investigate the influence of changes in anthropogenic sources of nitrates or natural factors on groundwater vulnerability. Two predictive scenarios are investigated. In Scenario 1, the variation in time of nitrate contamination in groundwater and of urban nitrate sources and their distribution over the plain for the period 2011 to 2020 is maintained equal as their evolution and distribution in the 2000s. To observe only the impacts of changes in urban nitrate sources, natural factors are considered stable and unchanged in the two decades. In Scenario 2, the possible evolution, both in time and in space, of groundwater depth is considered as an additional changing factor together with the evolution of nitrate contamination and urban nitrate sources. While more complicated scenarios can be realized, in Scenario 2, it is assumed that the variation of nitrate contamination in groundwater is the same as in Scenario 1, although groundwater depth changes could cause different nitrate concentration trends with respect to the assumed variability.

Results and discussion

Generalization of the explanatory variables

The principal phase of the WofE technique is the generalization of the explanatory variables combined with the computation of the positive and negative weights, and their derived contrast (Bonham-Carter 1994). It enables an assessment of the influence of the variables under consideration on groundwater contamination. The analysis executed for each model reveals that (Table 1):

- Natural factors, such as soil protective capacity, groundwater depth, groundwater velocity and hydraulic conductivity of the vadose zone, influence groundwater vulnerability, confirming results from previous studies (e.g., Nolan et al. 2002; Masetti et al. 2008; Sacchi et al. 2013; Sorichetta et al. 2013);
- Urban nitrate sources are prevalent on agricultural sources in the Lombardy Plain area. This outcome is strictly related to the distribution of both anthropogenic activities and natural factors, whose combination can mitigate or facilitate nitrate contamination (Sacchi et al. 2013);
- The direct relation between the increasing spread of urban areas (QuikSCAT-DSM variation) and the occurrence of increasing nitrate concentration in groundwater demonstrates the link between the urban development and the increase of contamination in the shallow aquifer (Stevenazzi et al. 2015). Anomalies in the variation of population density indicate a tendency that people like to move away from over-crowded urban areas and sprawl to more open suburban areas with natural or agricultural surroundings (Stevenazzi et al. 2015), demonstrating the occurrence of the urban sprawl phenomenon in the Po Plain area (EEA 2006);
- Combining static and dynamic variables (i.e., both extension and development of urban areas in the decade of the 2000s) reveals that either the occurrence or the increase of nitrate contamination in groundwater can be related to both the presence and the evolution of nitrate sources of contamination, especially related to urban activities.

Tab. 1 - Relationships between explanatory variables and groundwater vulnerability to nitrate contamination according to the spatial, temporal and spatio-temporal models.

Tab. 1 - Relazione tra i fattori predittivi e la vulnerabilità degli acquiferi alla contaminazione da nitrati secondo i modelli "spaziale", "temporale" e "spazio-temporale".

	Relationship with groundwater vulnerability				
Explanatory variable	**Spatial model**	**Temporal model**	**Spatio-temporal model**	**Predictive spatio-temporal model**	
				Scenario 1	Scenario 2
STATIC					
Soil protective capacity (-)	Inverse	Not used[1]	Not used[1]	Not used[1]	Not used[1]
Groundwater depth (m)	Direct	Direct	Direct	Direct	-
Hydraulic conductivity of the vadose zone (m/s)	Direct	Direct	Direct	Direct	Direct
Groundwater velocity (m/s)	Direct	Direct	Direct	Direct	Direct
QuikSCAT-DSM (dB) [2]	Direct	-	-	-	-
Population density (people/km^2) [2]	Direct	-	-	-	-
Nitrogen load (kg/ha*year)	Not used[3]	-	-	-	-
DYNAMIC					
QuikSCAT-DSM variation (dB/year) [2]	-	Direct	-	-	-
Population density variation (people/km^2) [2]	-	Direct	-	-	-
Nitrogen load variation (kg/ha*year)	-	Not used[3]	-	-	-
STATIC&DYNAMIC					
QuikSCAT-DSM combination (-)	-	-	Direct	-	-
QuikSCAT-DSM combination [2020] (-)	-	-	-	Direct	Direct
Groundwater depth [2020] (m)	-	-	-	-	Direct
[1] Relationships for soil protective capacity are not reported because of its low statistical significance in the analysis.					
[2] Population density and QuikSCAT-DSM are used in alternative as proxies for urban nitrate sources.					
[3] Relationships for nitrogen load are not reported because of its lack of physical significance in the analysis.					

Groundwater vulnerability maps and map of severity

In the WofE technique, the combination of the significant explanatory variables allows the generation of the predictive probability maps (Bonham-Carter 1994). The resulting maps represent groundwater vulnerability to nitrates in the Lombardy Plain area. Following the flowchart of the time-dependent approach shown in Figure 1, each model has been realized and each resulting map is shown in Figure 4.

The groundwater vulnerability map obtained through the spatial model represents different degrees of vulnerability when the combination of natural and anthropogenic factors involves a given absolute level of nitrate contamination (Fig. 4a). Instead, the groundwater vulnerability map obtained through the temporal model represents different degrees of vulnerability when the combination of natural and anthropogenic factors involves a deterioration of groundwater quality (Fig. 4b). Thus, the spatial model represents a static condition, since factors influencing groundwater vulnerability are not time-dependent, and it refers to a specific time (i.e., the year 2011). Whereas the temporal model represent a dynamic condition, since the evolution in time of the same factors is taken into account for the generation of the model, and refers to a specific period of time (i.e., from 2000 to 2011).

Combining these two maps is possible to consider both the static and the dynamic conditions (Stevenazzi et al. 2017a). The spatio-temporal model allows representing vulnerable areas due to a given absolute level of nitrate contamination and/or increasing trend of nitrate concentrations (Fig. 4c).

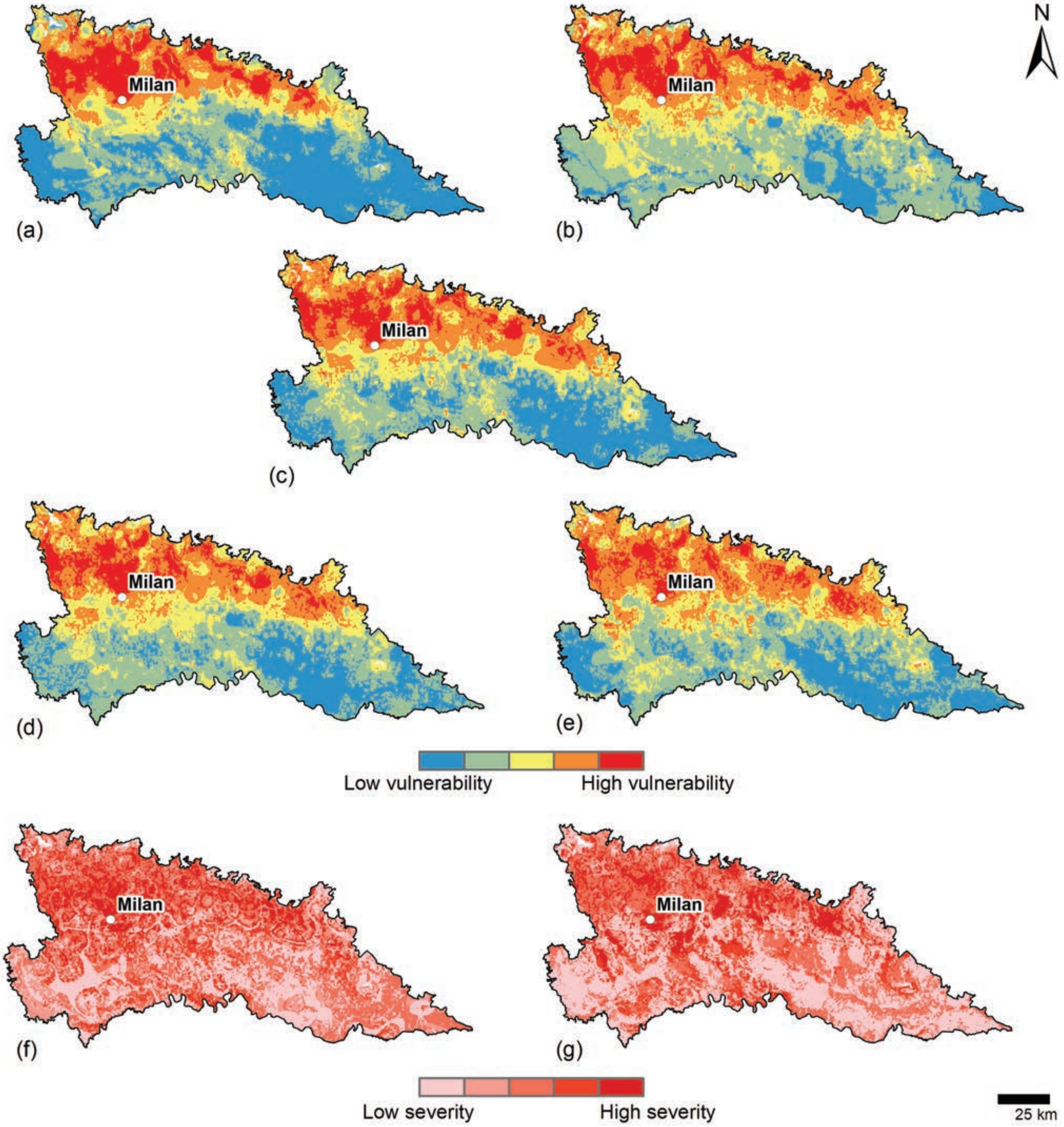

Fig. 4 - Groundwater vulnerability maps (a-e) and maps of severity (f-g). (a) Spatial model, (b) Temporal model, (c) Spatio-Temporal model, (d) Predictive Spatio-Temporal model - Scenario 1, (e) Predictive Spatio-Temporal model - Scenario 2, (f) Map of severity - Scenario 1, (g) Map of severity - Scenario 2. Vulnerability degree increases from blue to yellow to red colors. Severity increases from pink to red colors

Fig. 4 - Mappe di vulnerabilità degli acquiferi (a-e) e mappe di criticità (f-g). (a) Modello spaziale, (b) Modello temporale, (c) Modello spazio-temporale, (d) Modello spazio-temporale predittivo - Scenario 1, (e) Modello spazio-temporale predittivo - Scenario 2, (f) Mappa di criticità - Scenario 1, (g) Mappa di criticità - Scenario 2. Il grado di vulnerabilità aumenta dal blu al giallo al rosso. Il grado di criticità aumenta dal rosa al rosso.

The spatio-temporal model refers to both the status in 2011 and the evolution from 2000 to 2011 of factors influencing groundwater vulnerability. Despite the map is the result of a combination of natural and anthropogenic factors, the distribution of the vulnerable areas mainly reflects the distribution of urban areas characterized by the presence of a notable and continuous urban pattern in 2011 and/or an increase in extension or modifications of their pattern in the period 2000-2011.

As for the spatio-temporal model, the predictive spatio-temporal model represents potential vulnerable areas reflecting either the presence of contamination or the deterioration of the aquifer, due to hypothetical changes of land use or natural factors (e.g., different grow rates of urban areas or groundwater depth variations, Fig. 4d, e). The predictive spatio-temporal model refers to both the hypothesized status in 2020 and the hypothesized evolution from 2011 to 2020 of factors influencing groundwater vulnerability. Two scenarios have been investigated: Scenario 1 evaluates the influence of changes of anthropogenic sources of nitrates on groundwater vulnerability (Fig. 4d) and Scenario 2 evaluates the influence of changes of anthropogenic sources of nitrates and of groundwater depth (Fig. 4e).

It is interesting to note that the distribution of the vulnerable areas in the present and in the future is similar (Fig. 4c VS Fig. 4d, e). The most vulnerable areas are located in the northern sector, whereas the less vulnerable areas are located in the southern sector. Despite a sensible reduction of the most vulnerable areas (in red) in the 2020-projections, a reduction of the less vulnerable areas (in blue) occurs too. Such reductions correspond to an expansion of the medium vulnerable classes.

The maps of severity (Fig. 4f, g) represent the critical areas at 2020, based on the vulnerable areas at 2011 and considering the evolution of natural and anthropogenic conditions in the period 2011–2020. Since groundwater vulnerability refers to a specific time in a given area (Vrba and Zaporozec 1994), the term "vulnerability" may not be appropriate when comparing two maps referred to different moments. For this reason, the term "severity" is used in this study to describe areas where the probability of groundwater quality deterioration occurring in the future is higher or lower compared to the previous conditions. For example, a high severity occurs if the vulnerability degree at 2011 is high or if there is an increment of the vulnerability degree between 2011 and 2020.

The maps of severity show that groundwater contamination remains a major problem in the northern sector of the study region, with the prevalence of high classes of severity. Despite the southern sector is generally the less vulnerable in the study area, medium-high levels of severity are present in some areas in the central and east-southern sectors. This highlights potential problems in groundwater quality if land-use policies in the period 2011–2020 are maintained as in the period 2000–2011 (i.e., at the status quo). Comparing the maps of severity of Scenario 1 (Fig. 4f) and Scenario 2 (Fig. 4g), it is evident that the hypothesized change of groundwater depth in the period 2011–2020 has positive effects on the distribution of severity degrees, determining the prevalence of low severity degrees in the study area, especially in the southern sector. This highlights the importance of natural factors in influencing the fate of contaminant in groundwater and remarks that a better comprehension of their evolution in time allows investigating more realistic and complex future scenarios (e.g., extreme climatic conditions).

Innovation of the proposed methodology

The time-dependent approach meets the EU requirements on groundwater quality and protection by taking into account both the recent status and the evolution of groundwater contamination. It allows identifying areas simultaneously affected by high levels of contamination and increasing concentration trends and determining which natural and anthropogenic factors are the most responsible for groundwater deterioration. The approach takes advantages of statistical methods for assessing groundwater vulnerability, including also the time dimension. This innovation enable an evaluation of the efficiency of land use and urban development decision on groundwater protection to achieve mid-to-long term safeguarding levels of groundwater quality (Lavoie et al. 2015). The implementation of the time-dependent approach in the Lombardy Plain area has demonstrated what can happen to groundwater resources in the context of a continuous development of urban areas (Scenario 1) and in the case of both a persistence of the urban sprawl phenomenon and a sensible variation of one hydrogeological parameter (Scenario 2). Thus, the approach allows evaluating what can happen to groundwater resources if policies (i.e., land use and water resources management) are maintained at the status quo or if new measures are introduced as natural factors change under climatic or anthropogenic stresses.

This methodology can account for the innovative use of QSCAT-DSM dataset (Nghiem et al. 2009), which has proven to be a reliable variable to be used in groundwater vulnerability assessments as a proxy for urban nitrate sources. QSCAT-DSM has the advantages of a worldwide coverage, a continuous data collection over a decadal period and a high resolution of 1 km^2 without spatial gaps. These issues are not completely achieved by population density or land use datasets. This is remarkable for those areas where there are insufficient or inaccurate data for population or land use and their changes, and thus satellite observations of urban change become particularly useful (Stevenazzi et al. 2015).

Conclusions

A time-dependent approach for groundwater vulnerability assessment has been developed to account for the recent status of groundwater contamination and its evolution in the Po Plain area of Lombardy Region. Such an approach would meet the requirements of the recent EU Directives on groundwater quality and protection (WFD, 2000/60/CE and GWD, 2006/118/CE) by recognizing areas where groundwater suffers high contaminant levels and increasing trends in contaminant concentrations.

In a continuous evolving environment, the inclusion of the time variable in groundwater vulnerability assessment can offer new perspectives in assessing the impacts of actual and potential land-use planning and policies on groundwater resources. In particular, it emerged that existing and future satellite scatterometer data can be used to make and update maps of groundwater vulnerability as urbanization accelerates across the world.

Through this approach, decision makers can count on a high-level guide on the compatibility of a given policy or activity in a certain area, to mitigate new groundwater diffuse contamination occurrences or avoid the deterioration of the existing ones. The global result is an improved protection of groundwater quality with clear advantages for the environment and for groundwater-dependent ecosystems and a general benefit to society, especially in terms of sustainable costs.

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