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ORIGINAL ARTICLE

A new decision-oriented groundwater protection model: framework and implementation in a case study in Morocco

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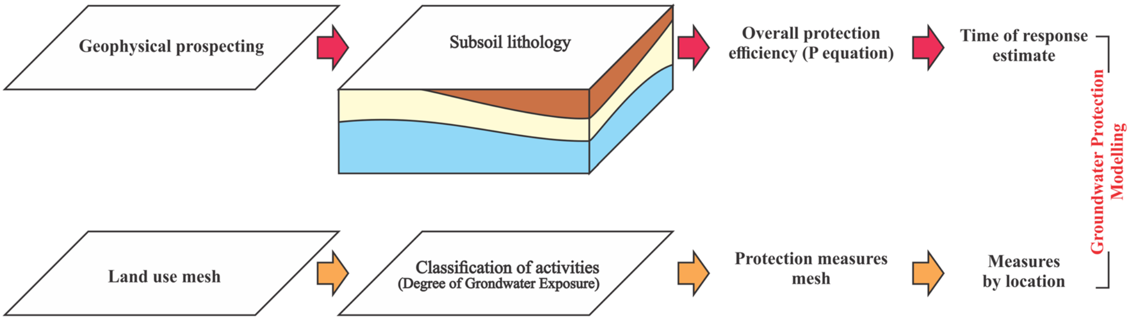
Abstract

Groundwater protection models systematically assess the vulnerability of the entire aquifer. They require extensive but often scarce or expensive data to produce guidelines that are barely comprehensible to policymakers. A better alternative would be a cartographic fragmentation of the landscape to target locations where polluting activities exist or are expected and simplify the model so that it is easier to implement and leads to measurable, realistic, and timely actions. In this paper, we propose a new flexible user-oriented Groundwater Protection Model (GPM) that adapts to land use changes to anticipate protection measures. It was designed to provide two key elements: (i) the response time which is a function of thickness and hydraulic conductivity of the unsaturated zone, and (ii) the protection measures that depend on the type of contaminant likely to penetrate from a surface spill. GPM was tested in a case study in Morocco where targeted geophysical surveys filled the data gap. The results are consistent with previous classic studies and have the advantage of being cost-effective and spatially specific. For this, we recommend its broad application to improve the management and protection of groundwater, particularly in the event of a lack of means or data.

Graphical abstract



Keywords Groundwater · Protection · Vulnerability · Model · Decision-making

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Introduction

The assessment of groundwater vulnerability and risk is of unquestionable importance for water management, especially in developing countries that undergo water shortage problems combined with strong socio-economic and political pressures that lead to a pollution spread which disregards protective frameworks. The most pertinent visions of Aller et al. (1987) and Foster (1987) became the inspiration for most hydrogeologists who sought a direct impact on territorial strategies, protection of resources, and improvement of social welfare. Since then, most of the papers have shown outstanding outputs through insulated or comparative case studies while few have focused on developing and modelling approaches to improve the understanding and promote technical progress and innovation that have reach and enthuse large numbers of researchers (Benabdelouahab et al. 2018; Machiwal et al. 2018; Wachniew et al. 2016).

However, the aquifer vulnerability concept still has two quite unresolved scientific and decisional dimensions (Gray et al. 2014; Machiwal et al. 2018; Voigt et al. 2004). From the scientific point of view, it refers to the susceptibility to being adversely affected by an imposed contaminant load from the land surface (Vrba and Zaporozec 1994; Foster et al. 2002; Machiwal et al. 2018). This concept has proved a useful communication bridge (about groundwater quality protection needs) between scientists and policy-makers, thus, enabling the application of land use constraints and pollution control measures (Foster et al. 2013). Nevertheless, the abundance of assessment models causes an ambiguous perception which often leads to conflicting results or even lack of scientific evidence (Frind et al. 2006; Lasagna et al. 2018; Stevenazzi et al. 2017). As proof of this ambiguity, generalist models (e.g. GOD (Foster 1987)) which were originally performed to qualify the vulnerability of the extensive British aquifers are endorsed by several authors for small aquifers where lateral and vertical lithological variations are frequent (Aboulouafa et al. 2020; Maria 2018; Rukmana et al. 2020). In addition, some authors (Busico et al. 2017; Jesiya and Gopinath 2019; Noori et al. 2019; Omotola et al. 2020; Wu et al. 2018) have improvised parametric modifications to the original models established after exhaustive and meticulous investigations (i.e. DRASTIC and SINTACS), motivated by the lack or incompatibility of the data at their disposal. For this reason, it is not clear whether this improvisation based on isolated case studies can be extrapolated as with the original models extensively tested. It is true that comparing the advantages and limitations of models, and identifying the most suitable for an area of interest is crucial (Shrestha et al. 2017), however, many authors carry out comparative studies but fail to conclude the most suitable model for lack of validation or uncertainty (Hermanowski and Ignaszak 2017; Lasagna et al. 2018; Luoma et al. 2017). Faced with this scientific ambiguity, it is essential to decide on the most suitable evaluation model (Aller et al. 1987; Aslam et al. 2018; Civita et al. 2000). However, although some models are well designed, they are difficult to apply due to lack of required parameters, especially in scarce data areas; thus the importance of defining the key parameters (Casas et al. 2008; Kirsch 2009; Stempvoort et al. 1993). Admittedly, the latter are the thickness and hydraulic properties of the unsaturated zone, which affect the percolation of contaminants into the productive aquifer (Díaz et al. 2008; Li et al. 2017; Omosuyi and Oseghale 2012). In many cases (e.g., small, intramountain, or multi-layered aquifers), the application is complex due to frequent lateral and vertical lithological variations which require a more dense and detailed data mesh (Himi et al. 2017). This is only possible thanks to geophysical prospecting as a scientifically accepted and cost-effective tool (in correlation with existing drilling data to avoid measurement or interpretation errors) (Martorana et al. 2018; Parsekian et al. 2017).

From the decisional point of view, the growing impact of the scientific outputs could raise awareness and lead to tangible protection measures despite a persistent gap of understanding and perception (Ardaya et al. 2019; Pluchinotta et al. 2019; Salhi et al. 2020c). It has been argued that this gap is a consequence of the pressure exerted by the executive branch on a repressed scientific community resulting in a loss of the capacity to achieve synergistic cooperation which, instead, turns into a mechanism of worsening of efficiency and creativity which generates unclear ideas and disruption of mutual perception (Mani et al. 2013; Poege et al. 2019). For instance, policy-makers tend to achieve the sustainable development goals by seeking quick and cost-effective scientific advice which forces researchers, therefore, to base their orientations on parametric evaluation models, the simplest and most popular, but which often suffer from both insufficiency and cumbersome in terms of time and resources (Allouche et al. 2017; Salhi 2008). In this regard, guidelines should henceforth address three specific keys to decision making: namely time, cost, and location. Furthermore, even if some papers produce reliable results, they require advanced skills in analysis and assimilation of cartographic and explanatory data which policy-makers do not, necessarily, have. Therefore, despite many ingenious assessments that can carefully incorporate all key parameters, constraints are still identifiable with respect to the level of explicit detail (cartographic and alphanumeric), consistency of applicability to any hydrogeological setting, and post-vulnerability and risk assessment actions. As a result, policy-makers often express great ambiguity in relation to the actions to be taken and the response times (Benabdelouahab et al. 2018; Gray et al. 2014; Salhi et al. 2020b; Tziritis et al. 2020; Zwahlen 2003).

With this in mind, the contribution of this paper is to consider both the scientific and decisional dimensions to provide a new relevant tool that simplifies the substantial assessment into clear and concrete practical actions. We carefully document the rationale for obtaining this tool and the steps for its application. Also, there is a section about the results of implementation in a case study later in the paper.

Materials and methods

This paper suggests a user-oriented Groundwater Protection Model (GPM) for application in land use and environmental management, and that is scientifically legitimate using appropriate definitions. The GPM is designed to be meaningful to a broad audience and targets feasible protective measures and the time available to activate them. The purpose is to improve the practicality of groundwater protection through a screening tool to identify where detailed field investigation and priority protection measures are most needed to counter a pollution threat. In short, it has been designated a tool that provides two key elements: the response time and the protection measures to be taken.

Time of response estimate

First of all, the assessment depends on the cartographic fragmentation of the landscape, hence the importance of defining the effective mesh size. The latter is inversely proportional to the level of precision required, to the costs and to the complexity of the lithological variations. For this reason, it is recommended to use a dynamic mesh size according to the available economic and technical means, and to the variation of land use and lithological patterns. For instance, a 1 km mesh is recommended in monolayer homogeneous aquifers with sparse anthropogenic activities and/or scarce technical and economic resources. Alternatively, a smaller mesh (200–500 m) should be considered. The location of the pixel in the mesh must be indicated unambiguously. An alphanumeric positioning language that can be assimilated by the general public should be favored over a conventional coordinate system (Fig. 2).

The response time is estimated proportionally according to the retention time of the contaminant in the unsaturated zone. Indeed, the retention time is proportional to the thickness and inversely proportional to the hydraulic conductivity (Akpan et al. 2015; Christiansen et al. 2014; Kirsch 2006; Luoma et al. 2017). In most models, both parameters are essentially extracted from borehole data which are often scarce or poorly distributed (Fig. 1). Alternatively, geophysical prospecting (e.g. resistivity methods) can provide both accurately and rapidly, especially since hydraulic conductivity is inversely proportional to clay content, which is proportional to electrical conductivity in detrital aquifers (Kalinski et al. 1993; Kirsch 2009).

According to SGD model, the aquifer protection depends on water capacity of the soil (AWC), percolation rate factor (W), rock type factor (R), and thickness of the unsaturated zone (T) (Hölting et al. 1995). The last two parameters can easily, even upon request, be obtained from geophysical data (in complementarity with borehole logs). AWC can logically be excluded from the assessment since it is based on natural soil protection down to 1 m depth which is, in urban and built areas, generally removed. Furthermore, soil spatial information is often unavailable and/or inaccurate in developing countries (van Zijl 2019). W factor could be assessed based on the available field data (artificial recharge rates and/or climatic records) or online products (e.g. Rainfall reanalysis) through well-known ways (Custodio and Llamas 1976; Szilagyi and Jozsa 2013).

With this adjustment, an efficient improved model is obtained, especially in built-up areas, with a set of required parameters easily found even in areas with scarce data. The overall protection efficiency (P) is calculated according to the following equation:

$$P = W \cdot \sum_{i=1}^{n} R_i \cdot T_i \tag{1}$$

where, W is the percolation rate factor (unitless), R is the rock type factor (unitless), and T is the thickness (in meters) of the corresponding layer of the unsaturated zone (Voigt et al. 2004). First, the electrical resistivity of the different layers of the subsoil can be interpreted (in correlation with borehole logs) into types of rock according to the grain size classes, from which the R factor is deduced according to Table 1. Second, the R factor of each layer is multiplied by its thickness in meters, then we sum them all. Third, after calculating the annual recharge (mm/year), the value of the factor W, concluded from Table 1, is multiplied by the sum to obtain the value of P. The latter is subdivided into five classes which are correlated to different approximate retention intervals within the unsaturated zone (Table 1) (Hölting et al. 1995; Kirsch 2009; Voigt et al. 2004).

With this in mind, the response time is a logical ratio proportional to the estimated retention time. In general, management plans are divided into three intervention phases: immediate, short term and medium to long term (Dehghani et al. 2019; Kutter and Neely 1999; USDA 2014). According to the same logic, when the retention time does not exceed a few months to a maximum of 3 years, immediate intervention should be required taking into consideration that this intervention is likely to undergo a bureaucratic process of

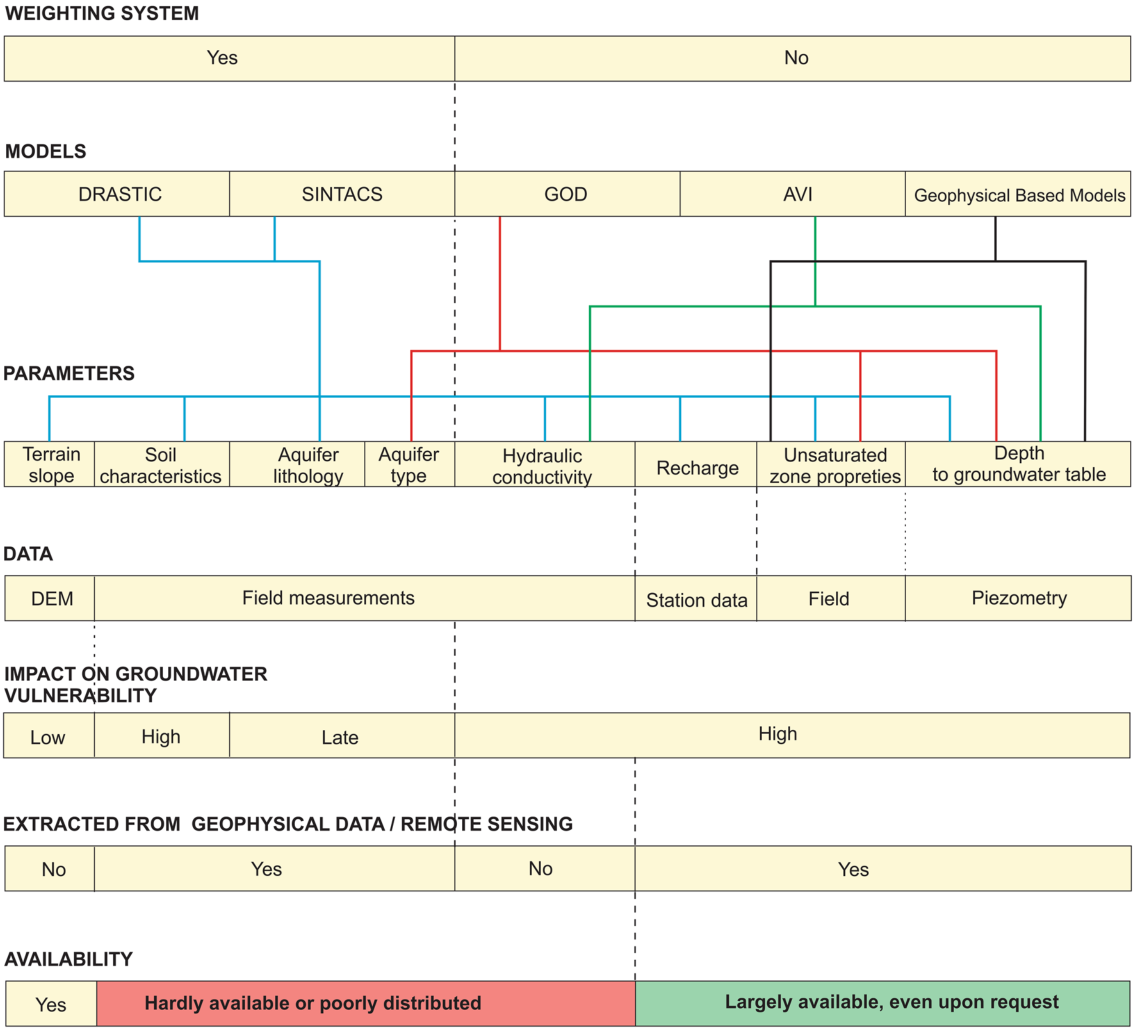
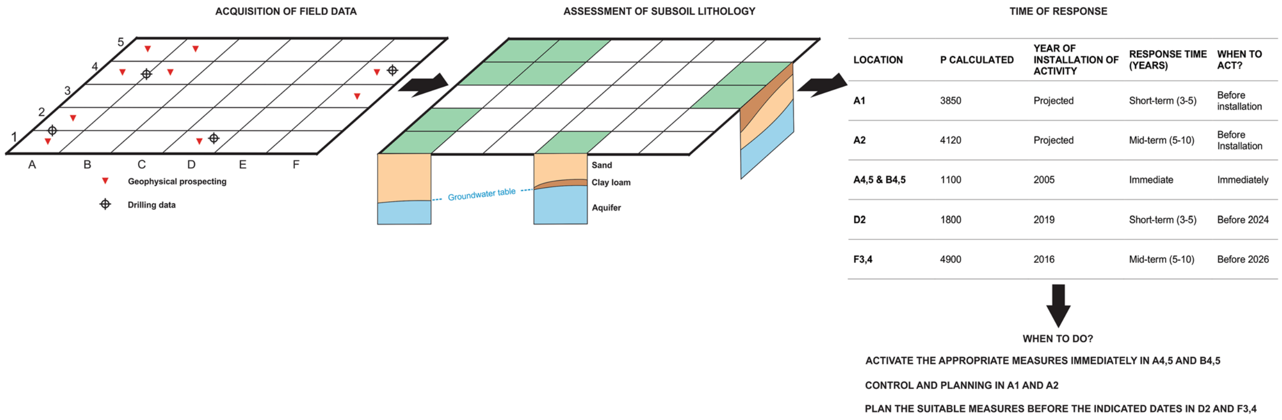


Fig. 1 Critical review of the common empirical models. There is a large array of empirical models to assess the intrinsic groundwater vulnerability based on hydrogeological parameters which, later, are combined through a cartographic process by the assignment of intervals and/or classes to produce a vulnerability index map. The application of empirical models is often complicated due to their limitations or to the deficiency of accurate and well distributed data. The geophysical models are simpler and reliable

Table 1 Assessment of the response time corresponding to the approximate retention time in the unsaturated zone calculated based on the multiplication of the rock type factor (R), the percolation rate factor (W), and the thickness of rock cover above the groundwater table (T) according to Eq. 1 (adapted from Hölting et al. 1995; Kirsch, 2006; Voigt et al. 2004)

Grain size class	R factor	Groundwater Recharge (mm/y)	W factor	P classes	Approximate retention time in the unsaturated zone	Response time (starting from the settlement of pollutant activities)
Clay	500	<100	1.75	>4000	>25 years	In 5 to 10 years (mid-term plan)
Clayey loam	300	100.1–200	1.50	2000.1–4000	10–25 years	
Clayey silty loam	240	200.1–300	1.25	1000.1–2000	3–10 years	Within 3 years (short-term plan)
Sandy loam	180	300.1–400	1.00	500.1–1000	Some months to 3 years	Immediate action
Sandy silt	120	>400	0.75	≤ 500	Some days to 1 year	
Loamy sand	90					
Slightly loamy sand	60					
Sand	25					
Gravel and/or breccia	5					



LOCATION	P CALCULATED	YEAR OF INSTALLATION OF ACTIVITY	RESPONSE TIME (YEARS)	WHEN TO ACT?
A1	3850	Projected	Short-term (3-5)	Before installation
A2	4120	Projected	Mid-term (5-10)	Before Installation
A4,5 & B4,5	1100	2005	Immediate	Immediately
D2	1800	2019	Short-term (3-5)	Before 2024
F3,4	4900	2016	Mid-term (5-10)	Before 2026

WHEN TO DO?

ACTIVATE THE APPROPRIATE MEASURES IMMEDIATELY IN A4,5 AND B4,5

CONTROL AND PLANNING IN A1 AND A2

PLAN THE SUITABLE MEASURES BEFORE THE INDICATED DATES IN D2 AND F3,4

Fig. 2 Assessment of the available time of response based on the retention time of the contaminant in the unsaturated zone

planning and implementation which may last a few months. Under better circumstances, response time can be planned over multiple budget years, when retention time spans more than three years (Table 1). Of course, the response time is calculated from the moment of installation of the polluting activity. Thus, it is important to learn about this variable when deducting the intervention deadline.

The close link between land use management and groundwater protection has long been recognized, but not concretely translated into integrated policies and interventions, as the utopia of scientific assessment converges on summary orientations while planning and management require concrete guidance fragmented in space and time (Foster 2018; Salhi et al. 2020a; Yu et al. 2018). With this in mind, our scientific responsibility enables us to objectively link the response times with the retention time of the contaminant at the level of the unsaturated zone (Fig. 2). The goal is to adapt the intervention times reasonably to provide the possibility of temporally programming the protective measures according to the real conditions (in case of existing activities) and future projections. This temporal phasing is accompanied by a package of measures per location as shown in the next section.

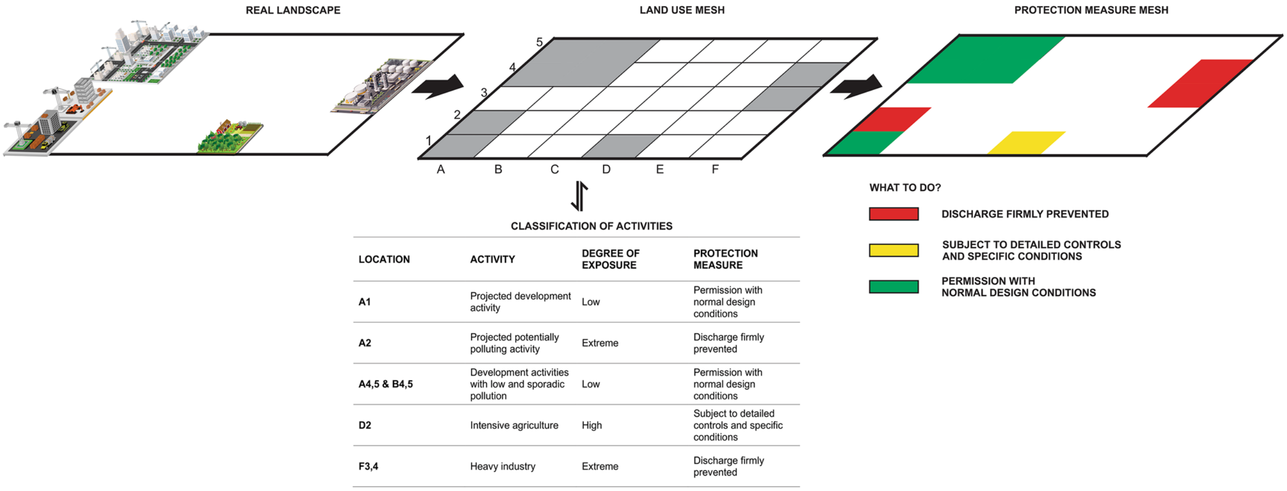
Protection measures

It was explained previously that the model implementation process starts with the subdivision of the land of interest (aquifer) according to a mesh established according to the needs and the available means. It is not necessary to apply the model on the whole aquifer but only in the pixels where dangerous activities are installed or projected (since it is addressed the vertical infiltration of pollutants). The first step, described above, consists in the acquisition in the selected pixels of the geophysical data (prospecting and/or borehole logs) necessary for the calculation of the P factor, from which the response time is deduced.

It is observed that the other models consider the concept of protection as a problem for the future taking into account mainly the projected activities. This disregard for activities already installed makes the implementation of prospective management plans ineffective because often the actual impact of these activities already exists (Bricker et al. 2017; Dillon et al. 2020). For this reason, it is recommended in the latter case to calculate the action timing for the concerned pixels from the year the activity was installed. (Fig. 2). At the mesh level, the location of the pixels where the activities are located or projected must be indicated according to the same alphanumeric positioning language used when estimating the response time.

Subsequently, the protective measures to be taken for each of the selected pixels must be indicated according to the degree of exposure resulting from the corresponding activity (Fig. 3). The protection measures will vary according to the degree of exposure of the productive aquifer which depends on the intrinsic vulnerability (taken into account previously in the estimation of the response time) but especially on the type of contaminant likely to penetrate from the surface following an intentional (or not) anthropogenic spill. There are three categories of exposure (low, high, and extreme) according to the vulnerability of the productive aquifer, which also depends on the type of contaminant likely to penetrate (Foster and Garduño 2013). These degrees of exposure are:

- Low: when the aquifer is favoured by conditions which protect it from most pollutants except the persistent agents that are discharged regularly and abundantly. In this case, most activities can be allowed under normal design conditions, except dangerous chemical activities or similar.



WHAT TO DO?

- 🟥 DISCHARGE FIRMLY PREVENTED
- 🟨 SUBJECT TO DETAILED CONTROLS AND SPECIFIC CONDITIONS
- 🟩 PERMISSION WITH NORMAL DESIGN CONDITIONS

CLASSIFICATION OF ACTIVITIES

LOCATION	ACTIVITY	DEGREE OF EXPOSURE	PROTECTION MEASURE
A1	Projected development activity	Low	Permission with normal design conditions
A2	Projected potentially polluting activity	Extreme	Discharge firmly prevented
A4,5 & B4,5	Development activities with low and sporadic pollution	Low	Permission with normal design conditions
D2	Intensive agriculture	High	Subject to detailed controls and specific conditions
F3,4	Heavy industry	Extreme	Discharge firmly prevented

Fig. 3 Assessment of the groundwater protection measures according to the degree of exposure of the productive aquifer which depends on the type of contaminant likely to penetrate from the surface

- High: when the aquifer is vulnerable to several pollutants and the conditions do not allow the contaminant to slow down so that the unsaturated zone can dissolve or transform it. In this case, potentially polluting activities must be prohibited or subject to detailed controls, specific design conditions (depending on the laws in force), and continuous inspections.
- Extreme: when the aquifer is vulnerable to the majority of pollutants and the conditions for protection are minimal or absent. In this case, all potentially polluting activities must be prohibited or, in cases of high strategic necessity, allowed at low intensity and under absolute containment and continuous inspections.

To facilitate the assimilation of these measures, the mesh must symbolize for each pixel the proper protection measures according to a scale of three colors (green, yellow, and red). The simplified legend that will accompany the cartographic representation explicitly shows the actions to be taken (Fig. 3):

- Green: permission with normal design conditions.
- Yellow: subject to detailed controls and specific conditions.
- Red: discharge firmly prevented.

At the same time, a more detailed explanatory table can support the mesh. Finally, managers can get all the information necessary to activate preventive or corrective measures per pixel (i.e. per place of activity), namely: "what to do", "where" and "when". The definition of "how to do" will obviously have to be defined by the managers themselves according to the means in their possession, the law in force and the response time available.

Thanks to this model, it is possible to bridge a scientific and above all decision-making gap, by creating a link between protection measures and reaction time. To test and validate it in reality, the model was implemented in a real case study as explained in the following section.

Study area and data

Systematic implementation aims to provide authorities with a direct tool to adopt an effective protection strategy and raise awareness among citizens of environmental issues. to test the efficiency and validity of our model, an example of implementation was carried out in the aquifer of Ghis-Nekor in Morocco where hydrogeological data (permeability, transmissivity, recharge, etc.) are scarce and/or poorly distributed (Benabdelouahab et al. 2019; Salhi and Benabdelouahab 2017; Salhi et al. 2008). This limitation was overcome with abundant well distributed geophysical data (154 vertical electrical soundings (VES) and 22 electrical tomography profiles (ERT) correlated to 84 borehole logs), the detailed description of which and their positions were already described in one of our recent articles (Benabdelouahab et al. 2019).

ERT prospection was carried out under Wenner–Schlumberger mixed array configuration with a multielectrode resistivity meter (48 switch) of 480 m line length and a standard 10-m electrode spacing. Previously, VES monitoring was carried out according to the Wenner–Schlumberger mixed array configuration using different AB current electrodes spacing to allow different depths of investigation (94 VES of 3 to 4 km AB spacing, 53 of 6 km, and 7 of 10 km). The field data were interpreted on the basis of Resixp (Interprex 1996) and Res2Dinv (Loke 1997) software (for VES and ERT respectively) in correlation with the available adjacent borehole logs. These data have already been used in a recent geophysical characterization and are well distributed over the entire study area (Benabdelouahab et al. 2019), which favours the extraction of the information required by our GPM model in the pixels where the potentially polluting activities are installed or projected.

The studied aquifer fills a triangular tectonic structure that opens to the north towards the Mediterranean (Fig. 4). It is a 100 km^2 multi-layered alluvial system filled with deposits of sand, gravel, and pebbles, with frequent clay-silt passages. The aquifer plays a major role in meeting the increasing demand for drinking and agricultural water supplies to maintain social and economic balance, especially in a stressful hydroclimatic context (Salhi et al. 2019). The intrinsic vulnerability previously assessed showed the most sensitive locations and sounded the alarm on the serious negative effects of the uncontrolled landfill, existing industrial, tourism, socio-economic, and surface mining activities and the repercussions they may have on

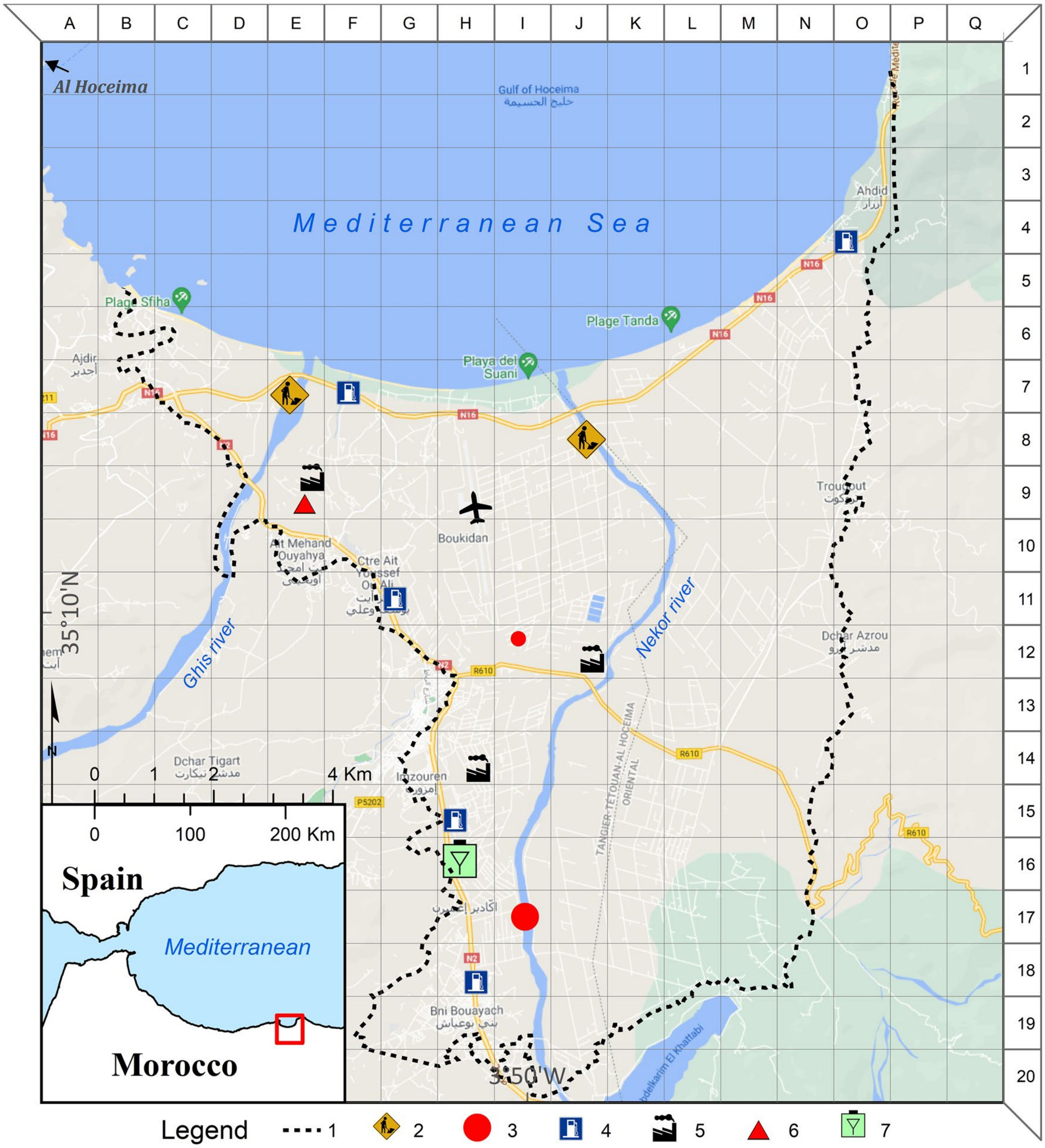


Fig. 4 Geographic location of the study area where fieldwork data is drawn on a topographic layer retrieved from Google Maps. 1: limits of the Ghis-Nekor aquifer; 2: open-air quarries for extracting gravel from the river; 3: uncontrolled discharge of solid and liquid waste; 4: fuel service station; 5: potentially polluting industrial activity; 6: slaughterhouse; 7: olive squwisser

the health, well-being and territorial development (Benabdelouahab et al. 2019; Salhi et al. 2008).

At the local administrative services, we revised the archives of industrial and service units located in the study area and those planned. A list has been drawn up with information concerning the location, dimensions, date of installation (actual or planned), type of activity and type of potentially polluting materials generated. This information has been verified in the field to ensure consistency and correct any eventuality.

Results

The study area was divided according to a reduced size pixel mesh of 1 km^2 into a total of 112 pixels. The non-uniformity of its shape made it preferable to even consider the pixels which are incompletely part of it. A unique alphanumeric marker has been assigned to each pixel to identify its location (Fig. 4). The application of the Ground Protection Model (GPM) enables the identification of 27 pixels that contain potentially polluting activities (Table 3), in which we used the aforementioned geophysical outputs to extract the data per pixel on the unsaturated zone (grain size class and thickness). The latter data have been converted to their corresponding values of R (rock type) and T (thickness) factors (Table 2). In parallel, the annual recharge was assessed according to the MODIS-aided net groundwater-recharge method at the same pixel-size (Szilagyi and Jozsa 2013). From there, the W (percolation rate) factor was deduced (Table 2). Consequently, we calculated the factor of the overall protection efficiency (*P*) at the pixel level according to Eq. 1. Obviously, the value of P was used to estimate the approximate retention time in each pixel (Table 2). Then, we compared the retention time with the date of installation of the activity, which allowed the assessment of the time response (when to act) at the pixel level (Table 3).

Afterwards, the activities were classified according to the degree of exposure of the corresponding pixel (i.e., Low, High or Extreme), which allowed the identification of protection measures at the pixel level (Table 3). Consequently, 9 scattered pixels where classified as of extreme (fuel service stations, olive squwisser, uncontrolled discharge of solid and liquid waste, slaughterhouse), 13 pixels as of high (open-air quarries for extracting gravel from the river, airport, urban agglomerations, and controlled industrial activity), and 5 as of low degree of exposure (extensive agriculture). Later, this information was simplified cartographically in three colours which indicate the places where the discharge is firmly prevented (Red = Extreme), where any discharge must be subject to detailed controls and specific conditions (Yellow = High), and where permission with normal design conditions are allowed (Green = Low) (Fig. 5).

Table 2 Protection measures corresponding to the degree of exposure of groundwater to pollution (adapted from (Foster et al. 2013))

Degree of exposure	Vulnerability of a productive aquifer	Contaminant type likely to penetrate	Protection measures
Low	Only vulnerable to persistent pollutants, mainly when widely and regularly discharged to ground	Nitrate, highly saline liquids, and risk of penetration of dense non-aqueous phase chlorinated organic compounds, and pharmaceutical products	Most development activities could be permitted and only subject to normal design conditions, except those that involve unlined lagoons or soak away drainage and/or handling groundwater hazardous chemicals
High	Vulnerable to various pollutants	Some fecal viruses, hydrocarbon fuels, extensive range of synthetic organic compounds, saline liquids and nutrients	Many potentially polluting activities must be prohibited or subject to detailed controls and specific conditions of contaminant and design, continuous monitoring and inspection
Extreme	Vulnerable to most water pollutants with rapid impact	Cryptosporidia, fecal bacteria and viruses, heavy metals, hydrocarbon fuels, extensive range of synthetic organic compounds, saline liquids and nutrients	All potentially polluting activities must be prohibited or only permited at low intensity with full containment and continuous monitoring and inspection

Table 3 Summary table of locations where hazardous activities are identified with indication of the response time (estimated from the calculation of the parameter P 'overall protection efficiency') and protective measures to be taken

Location	*W*	*R*	Depth to groundwater table	*T*	*P*	Response time	When the activity was installed	When to act?	Type of activity	Degree of exposure	Protection measure
E7	1,75	60	5	5	525	Immediate action	Over 10 years	Immediately	Open-air quarries for extracting gravel from the river	High	Many potentially polluting activities must be prohibited or subject to detailed controls and specific conditions of contaminant and design, continuous monitoring and inspection
E9	1,75	55	10	10	962,5	Immediate action	Over 10 years	Immediately	Potentially polluting industrial activity & slaughterhouse	Extreme	All potentially polluting activities must be prohibited or only permitted at low intensity with full containment and continuous monitoring and inspection
F7	1,75	180	5	5	1575	Within 3 years	Over 5 years	Immediately	Fuel service station	Extreme	
G11	1,75	170	12	12	3570	In 5 to 10 years	Over 10 years	Immediately	Fuel service station	Extreme	
H9	1,75	120	10	10	2100	In 5 to 10 years	Over 10 years	Immediately	Airport	High	Many potentially polluting activities must be prohibited or subject to detailed controls and specific conditions of contaminant and design, continuous monitoring and inspection
H10	1,75	120	12	12	2520	In 5 to 10 years	Over 10 years	Immediately	Airport	High	
H11	1,75	110	13	13	2502,5	In 5 to 10 years	Over 10 years	Immediately	Airport	High	
H14	1,75	134	30	30	7035	In 5 to 10 years	Over 10 years	Immediately	Potentially polluting industrial activity	High	
H15	1,75	98	40	40	6860	In 5 to 10 years	Over 10 years	Immediately	Fuel service station	Extreme	All potentially polluting activities must be prohibited or only permitted at low intensity with full containment and continuous monitoring and inspection
H16	1,75	121	50	50	10,587,5	In 5 to 10 years	Over 5 years	Immediately	olive squwisser	Extreme	
H18	1,75	92	90	90	14,490	In 5 to 10 years	Over 10 years	Immediately	Fuel service station	Extreme	
I12	1,75	143	14	14	3503,5	In 5 to 10 years	Over 10 years	Immediately	Uncontrolled discharge of liquid waste	Extreme	
I17	1,75	10	60	60	1050	Within 3 years	Over 10 years	Immediately	uncontrolled landfill	Extreme	

Table 3 (continued)

Location	*W*	*R*	Depth to groundwater table	*T*	*P*	Response time	When the activity was installed	When to act?	Type of activity	Degree of exposure	Protection measure
J8	1,75	161	6	6	1690,5	Within 3 years	Over 10 years	Immediately	Open-air quarries for extracting gravel from the river	High	Many potentially polluting activities must be prohibited or subject to detailed controls and specific conditions of contaminant and design, continuous monitoring and inspection
J12	1,75	151	14	14	3699,5	In 5 to 10 years	Over 10 years	Immediately	Potentially polluting industrial activity	High	
O4	1,75	30	1	1	52,5	Immediate action	Over 5 years	Immediately	Fuel service station	Extreme	All potentially polluting activities must be prohibited or only permitted at low intensity with full containment and continuous monitoring and inspection
G12, G13, G14	1,75	23	30	30	1207,5	Within 3 years	In expansion since over 10 years	Immediately	City	High	Many potentially polluting activities must be prohibited or subject to detailed controls and specific conditions of contaminant and design, continuous monitoring and inspection
H17, F18, G18, H18, G19	1,75	38	100	100	6650	In 5 to 10 years	In expansion since over 10 years	Immediately	City	High	
I18	1,75	38	57	57	3790,5	In 5 to 10 years	Projected	Before installation	Buildings	Low	Most development activities could be permitted and only subject to normal design conditions, except those that involve unlined lagoons or soak away drainage and/or handling groundwater hazardous chemicals
K16, K17, L16, L17	1,75	30	50	50	2625	In 5 to 10 years	Over 10 years	Immediately	Agriculture	Low	

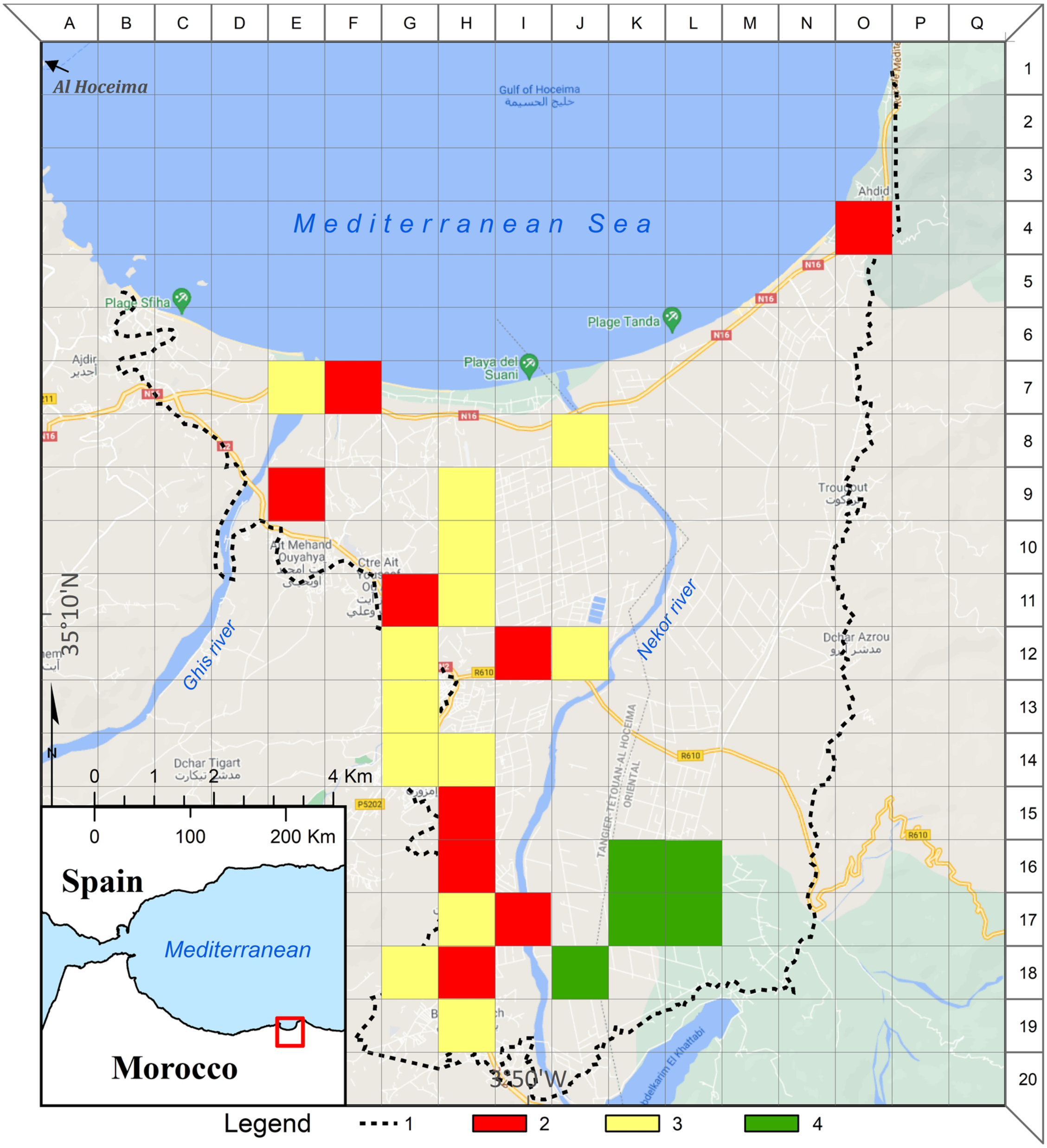


Fig. 5 Protection measure mesh of the Ghis-Nekor area. 1: limits of the Ghis-Nekor aquifer; 2: discharge firmly prevented in this location; 3: any discharge must be subject to detailed controls and specific conditions; 4: permission with normal design conditions

Therefore, managers have the three key pieces of information to solve the puzzle of effective and cost-effective management: where to intervene, when and how. The results are beyond those of classic vulnerability studies since they are both clear and focused.

In fact, the results are consistent with previous outputs which compared several empirical vulnerability assessment methods (Salhi 2008). These outputs concluded the DRASTIC method as the most recommended although it lacks some specific data in our case. The comparison between DRASTIC and the new model shows a concordance in terms of vulnerability assessment (degree of exposure) because the study of the nature and thickness of the unsaturated zone are similar even if DRASTIC has a rating system unfortunately inapplicable due to lack of data. The new model has the advantage of being direct, practical and spatially specific; it is not necessary to study the entire aquifer but specific places can be targeted by need and emergency.

Indeed, the statistical comparison between the two models was made at the pixel scale. Taking into account the unavailability of recent data on the permeability of the aquifer and that only 5 old reference points are available for this parameter, the comparison between the two models shows a similarity ranging from 61 to 74% (with and without permeability respectively) between the outputs of DRASTIC and GPM. The "nature of the aquifer" parameter is essential for DRASTIC even if its effect is late in terms of protection. Taking this into consideration, the resemblance between the two models decreases from 71 to 59%.

By eliminating the last two parameters of the DRASTIC equation (for the reasons mentioned above), we obtain a resemblance of 91%. Slight dissimilarities are attributed to DRASTIC's rating and weighting system which affects the model output.

Discussion

There is a pressing need to support research and innovation capacities and to develop knowledge and common innovative solutions for integrated water provision and management, to make these resources more climate resilient, efficient, cost-effective, environmentally and socially sustainable, stimulate a more sustainable and competitive industry, and to contribute to solving water scarcity, food security, nutrition, health, well-being and migration problems upstream. With this in mind, scientific guidelines should not be like a torrent flowing through the valleys, carrying rising foam, because the foam vanishes, and as for what is useful, it remains in the ground. Therefore, it is crucial to help secure water availability in terms of quality and quantity, as well as to improve sustaining an easy, cost-effective and fast decision-making process. This would be only possible through developing innovative and efficient solutions promoting their application to increase the governance and sustainability of water provision, providing environmental benefits and economic growth.

In this perspective, we recommend an innovative decision support system for planning adaptation to land use change and anticipating pollution. This groundwater saving solution (we call 'groundwater protection model' -GPM-) aims to alleviate water scarcity and protection management supported by forecasting systems which monitor the anthropogenic impact on productive aquifers. Current models of groundwater vulnerability and risk assessment address the entire aquifer system and use exhaustive but scarce or expensive means to produce barely comprehensible guidelines. As an alternative, GPM could be a faster and cost-effective tool that target only places where there is potential or anticipated polluting activities. It was designed to be easier for decision makers to understand, and with realistic, timely and measurable actions.

While there is a wide debate on the choice of the most suitable valuation model especially in small or complex aquifers, there is a consensus on the two key parameters that govern the protection of groundwater, namely the nature and the thickness of the 'protective layers' of the unsaturated zone (Díaz et al. 2008; Li et al. 2017; Omosuyi and Oseghale 2012; Stempvoort et al. 1993). By evaluating these layers, the idea was to provide a user-oriented tool that would be both scientifically valid and easy to understand, free from the complexity of certain current paradigms, and from the need to choose between methods according to scientific or technical criteria that are sometimes unclear or indecisive.

For the optimal implementation of the groundwater protection model, the following additional instructions must be followed (Foster and Garduño 2013):

- The best agricultural and industrial practices must be addressed, the use of certain pesticides banned, and incentives for land stewardship improved.
- The previously indicated measures concern both existing and new development activities, but additional controls should be phased in through negotiation for existing ones.
- The highly toxic, excessively mobile and persistent contaminants must be firmly prevented in terms of discharge.

Considering the context of climate change, the scarcity of resources, demographic growth, contamination, desertification, degradation of arable lands and loss of biodiversity and recently the pandemic, there is an urgent need to invest in improving the productivity, sustainability and learn from the lessons of nature and life. For instance, every day, the pandemic crisis teaches us eloquent lessons and gives us an opportunity to review our development strategies to ensure sustainability and efficiency. Disaster management plans need to evolve, taking into account the commandments learned from our tiniest enemy: anticipating the preparedness transcribed in detailed action protocols with certainty that (1) time is life, is better than wasting time naively fingers crossed to fall, lastly, into hesitant, improvised, unmeasured and cloned reactions that worsened infection and death statistics. We learned the hard way that (2) it is never enough prepared. The quarantine was globally admitted as the solution to face the spread of infections, and governments decisively imposed what it takes to persist with less bureaucracy, more coordination and supremacy. (3) For unusual threat, drastic measures. The pandemic impact seems selective according to the vulnerability of the infected, but this is a matter of perception because (4) everyone is vulnerable with different shapes and scales. Nations, communities and individuals saw the real value of things; everything could wait but (5) priorities first. Few of the decision-makers were taking scientists seriously while (6) it seems that the matter is proceeding with the adoption of convincing scientific arguments to prepare for the risks and mitigate them. Development patterns have produced wealth together with dangerous socio-economic gaps. In contrast, disasters can uncomfortably be helpful to learn improving infrastructure and build social resilience; (7) in every opportunity there is a threat, in every threat there is an opportunity.

Conclusions

Groundwater storage plays a fundamental role in shaping water security especially under global change stresses and increasing demand scenarios (Foster and MacDonald 2014). Furthermore, preventive measures are known to be more accessible and cost effective than attempts to reverse groundwater pollution, but the application of these measures raises several issues that border on policy, which poses a major challenge for planners as it requires options and actions that are locally tailor-made to suit different areas (Clemens et al. 2020; Lerner and Harris 2009). However, policymakers often express great ambiguity about what actions to take and when to respond, which creates an urgent need to simplify scientific guidance while preserving the accuracy and efficiency of the assessment. In the midst of the global pandemic crisis, the spread of infections has an exponential, unpredictable and spatiotemporally indeterminate curve. A new era lookup with profound social and economic changes to affect the international community at all levels; international cooperation, lifestyles, consumption and exchange modes will never be the same as one year ago. Consequently, the risk management schemes need to evolve based on this crisis explicit lessons. To this regard, scientists should adapt their guidance to meet the three required elements for decision making of any given action: time, cost and location. Obviously, scientific expertise will be of little use if it does not have a primary role in responsible decision-making, especially given the great complexity of groundwater protection topic.

In this article, we want to urge hydrogeologists to contribute actively and realistically to the growing interdisciplinary debate about water conservation. The assessment model that we suggest (GPM) has evolved to consider decision makers' perception and provide simple and direct guidance. It is based on the conviction of the need to frequently review disaster management plans, based on lessons learned from past events (Crowley 2017). It is useful to improve it locally by defining clear roles and responsibilities and by aligning and/or incorporating it into established directives.

GPM is a flexible screening tool which identifies where detailed field investigation and priority protective measures are most needed. It is a user-oriented alternative to classic models that targets realistic and measurable actions in a timely manner. It is reasonably suited to evolve alongside management plans by implementing protective measures that adapt to existing conditions and future projections.

It was tested in a case study in Morocco with results consistent with previous classic studies and with the advantage of being cost-effective, spatially specific, and meaningful to policymakers. Its broad application should improve groundwater management and protection, especially where there is a lack of means or data.

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Author contributions AS, MH, and ACP conceived and designed the work. AS, BS, and MH carried out the implementation. AS led the writing of the paper with contributions from all the authors.

Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Informed consent Map data copyrighted Google Maps contributors are available under Esri ArcGIS online tiles at https://mt1.google.com/vt/lyrs=mhl=enz={level}x={col}y={row}.

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