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Delimitation of the Perimeters of Protection of Groundwater Catchments of the Berrechid Aquifer (Morocco) through Hydrogeological Modeling

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Abstract

Over the last two decades, repeated dry periods across the country have clearly highlighted the weaknesses in the balance of needs and surface water resources. The latter are increasingly failing due to the large inter-annual rainfall variability and high exposure to evaporation. Because of their high inertial capacity, groundwater is less affected by interannual fluctuations and compensates for the irregularity of surface water availability. However, in addition to being overexploited, groundwater can be exposed to various types of pollution that can alter their quality, sometimes irreparably. The issue of delimiting the protection perimeters around catchments implies a local development policy that is coherent from the point of view of water management and spatial planning. The present work contributes to the delimitation of the perimeters of protection of groundwater catchments of the Berrechid aquifer. Thanks to the "particle tracking" method through the use of models MODPATH and MODFLOW interfaced to GMS 4.0 (Groundwater Modeling System Version 4.0), we delimited the closed protection perimeters, using the numerical MODPATH model, by drawing the 50-day isochrones. Within these perimeters, any bacteriological or chemical action is prohibited. We delimited also the distant protection perimeters (infinite transfer time) that serve as an extension to the closed protection perimeters (transfer time of 50 days). Feeding areas have been introduced to protect groundwater from substances with insufficient degradation and natural retention. The results obtained show that these wells (catchments (P1 to P9) intended for drinking water supply in the Berrechid region) could be contaminated if the part of the aquifer to the south, upstream of these wells, is polluted by persistent chemical substances. The agricultural activities must be controlled and regulated by the State authorities in order to avoid any risk of contamination of the new boreholes by phytosanitary products since Berrechid region is an agricultural zone.

Keywords

Groundwater, Perimeters of Protection, Modeling, Drinking Water, MODPATH, MODFLOW, Berrechid

1. Introduction

The Berrechid aquifer is relatively small in size compared to the water needs in the region (drinking and industrial water supply, irrigation, etc.). This should, a priori, encourage a particularly vigilant approach in its quantitative and qualitative management.

Adverse weather conditions and intensive groundwater exploitation have led to alarming decreases in levels in most of the semi-arid to arid zones of Morocco [1]. Per capita water reserves, which are already approaching the stress threshold of 1000 m^3/inhabitant/year, would be around 500 m^3/inhabitant/year in 2020 [2]. Several studies carried out in this respect have repeatedly highlighted the piezometric deficit, over-exploitation [3], quality degradation (many wells whose nitrate concentration was more than 50 mg/L [4] [5] [6]) and inadequate management of water resources.

Morocco's water resources suffer from a strong irregularity in space and time. The use of the mobilized resource is 91% to 94% for agriculture and only 6% to 9% for the supply of drinking water and industrial water. Long periods of drought combined with increased water needs are creating imbalances in quantity and quality in most aquifers in Morocco [7].

The MODFLOW modeling provided a better understanding of the hydrodynamic functioning of the Berrechid aquifer. During this modeling, the balance sheet turned out to be negative over the simulated period; this is due to increasing exploitation of groundwater, combined with dry climatic conditions [5] [8].

In order to prevent possible contamination of the new boreholes, and to guarantee at long-term good water production, it is important to set up protection perimeters around the boreholes. Therefore, perimeters of protection are an essential component of the groundwater management in the perspective of the sustainable development of Berrechid aquifer.

The protection of groundwater catchments (wells, boreholes, springs) against surface pollution is therefore becoming more and more essential. It consists in setting up, around these catchments, protection perimeters within which certain activities are prohibited or regulated.

2. The Study Area

The Berrechid plain, with a total area of 1600 km^2, is located south of Casablanca

(**Figure 1**). It is in the form of a bowl with a large radius of curvature of elliptical shape whose major axis is oriented substantially South West-North East, a length of about 60 km. It is limited to the South-East by the Settat Plateau, to the North-East by the Mellah Wadi Valley, to the South-West by the Souk-Jemaa Peninsula, and to the North-West by the Dune Sahel parallel to the shore

The Berrechid Plain fits into the category of arid to semi-arid regions. This character is however mitigated by the proximity of the ocean. The annual total rainfall is low and the number of rainy days is low. The dry period is spread over a six-month period, from May to October [10] [11].

The hydraulic network of the plain of Berrechid is very little developed, although many small wadis drain the plateau of Ben Ahmed-Settat and converge towards the center of the plain. These wadis are, from north-east to south-west, Asseïla, Aïda, El Ahmeur, Mazere and Tamdrost (**Figure 1**).

Among the studies that have focused on the Berrechid aquifer are Bolelli and Lesguisé ([12] [13]), Moullard and Hazan ([14]), Moniton and Nerat De Lesguisé ([15]), Hazan and Ferre ([16]), DGH ([10]), El Mansouri ([17] [18]), Kholtei ([4]), El Bouqdaoui ([5]) and El Bouqdaoui *et al.* ([6] [8]).

3. Material and Method

The following sections describe the material and the methodology used in this study.

3.1. Material

The establishment of the hydrogeological model of Berrechid aquifer required a database. The data used result from geological and hydrogeological works carried out on Berrechid aquifer ([4] [10] [19]). Hydrodynamic parameters such as hydraulic conductivity (permeability), coefficient of storing, porosity and Piezometric data have been used in the implementation of this model [8].

The delimitation of the perimeters of protection is based on the prohibition of any action likely to pollute the water table over a distance such that the transit time of the pollutants is sufficient enough for them to be degraded before reaching the catchment.

The protection perimeters of groundwater catchments are of three types: the immediate protection perimeter, the closed protection perimeter and the distant protection perimeter (**Figure 2**) [20].

Groundwater flow of the Berrechid aquifer modeling and protection perimeters determination were carried out using Visual ModFlow provided by GMS version 4.0 [21]. This software integrates three codes:

- ModFlow for the groundwater flow simulation;
- ModPath simulates the pathways of water particles;
- MT3D for mass transfer simulation.

The mathematical digital models of hydrodynamic flow are based on finite

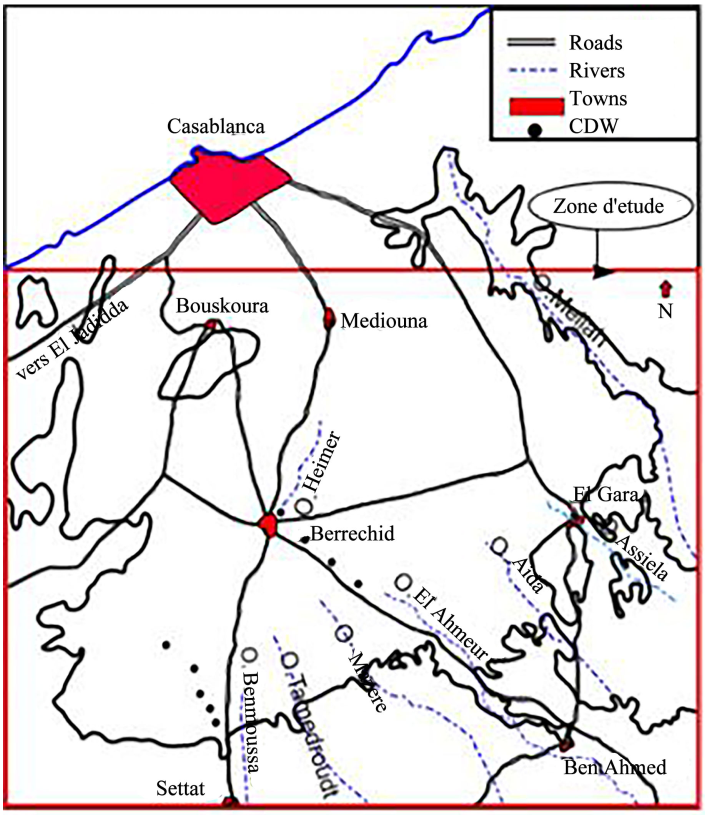

Figure 1. Location of the Berrechid plain [8] [9]. (CDW: Catchments of the drinking water).

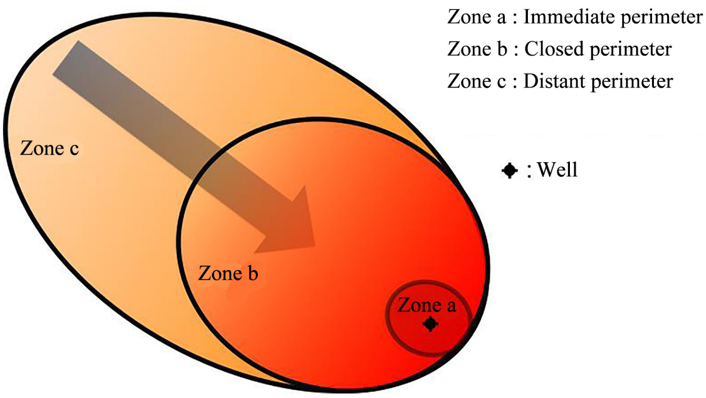

Figure 2. Presentation of perimeters of protection around a pumping well.

differences or finite elements. ModFlow allows to approximate flow equation solution through finite-difference method.

3.2. Methodological Approach

The selection of a protection perimeter analysis method is based on the general hydrogeological characteristics of the site, the phenomena to be studied, the results to be achieved and the degree of accuracy sought [22].

In general, the more the method allows the integration of the geological, hydrological and hydrogeological characteristics of the environment, the more precise it is [23].

The model is a numerical schematization of the hydrogeological system. It allows you to go from a natural complex system, the ground, to a whole model digital, the model development requires several steps, such as the determination of objectives to be achieved, the choice of the software used, the design of conceptual model [8], model calibration and finally the realization of predictive simulations (**Figure 3**).

The protection perimeters (closed and distant) can be delimited numerically using the MODPATH model using the so-called "particle tracking" tracing technique [6] from the piezometric distribution calculated by the MODFLOW flow model. This technique consists in following the advective trajectory of virtual particles placed in a flow field, thus making it possible to determine the flow lines and the associated transfer times. The path of the particles can be tracked in the direction of the flow (forward tracking) or "backward tracking". It is this last technique that we used after injection of virtual tracing particles in groundwater catchments.

4. Results and Discussions

The trajectories of the tracer particles are made using the model MODPATH integrated in GMS. These trajectories are determined mesh by mesh, by integrating in each mesh the real flow velocities calculated from the generalized Darcy's law by using the spatial distribution of the pizometric levels simulated by MODFLOW.

The hydraulic characteristics, namely the hydraulic conductivity and the storage coefficient of the aquifer used, are those obtained by calibration of the numerical model [8].

Figure 4 shows the distribution of the hydraulic conductivities restored by the calibration of the model showed five zones of permeabilities, with a maximum of 7.5×10^{-2} m/s and a minimum of 10^{-6} m/s, which respects the lithology of the corresponding formations [5].

The values of the storage coefficient from transient calibration vary between 5.0×10^{-4} and 0.2. These variations are due mainly to lateral facies changes in the aquifer and the type of flow of the aquifer.

Figure 5 shows the distribution of values of the storage coefficient obtained after calibration of the model under transient conditions [5] [8].

The simulations relate to the main groundwater catchments (P1 to P9) intended for drinking water supply in the Berrechid region (**Figure 6**).

4.1. Closed Protection Perimeters

In this section, we delimit the closed protection perimeters, using the numerical MODPATH model, by drawing the 50-day isochrones.

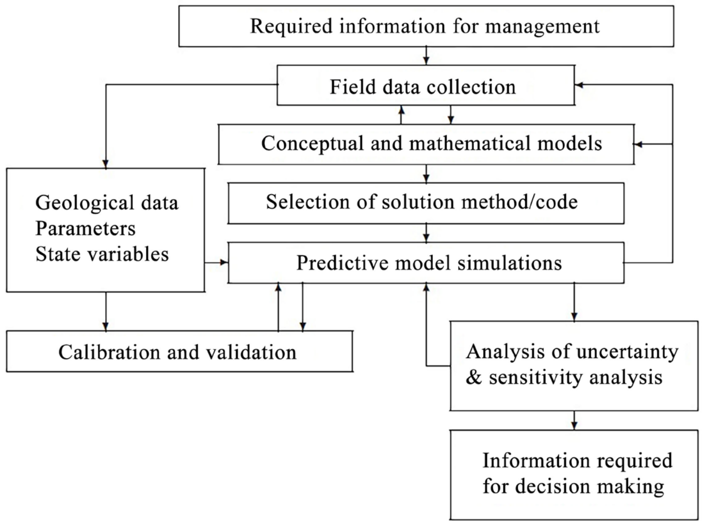

Figure 3. The modeling process [24].

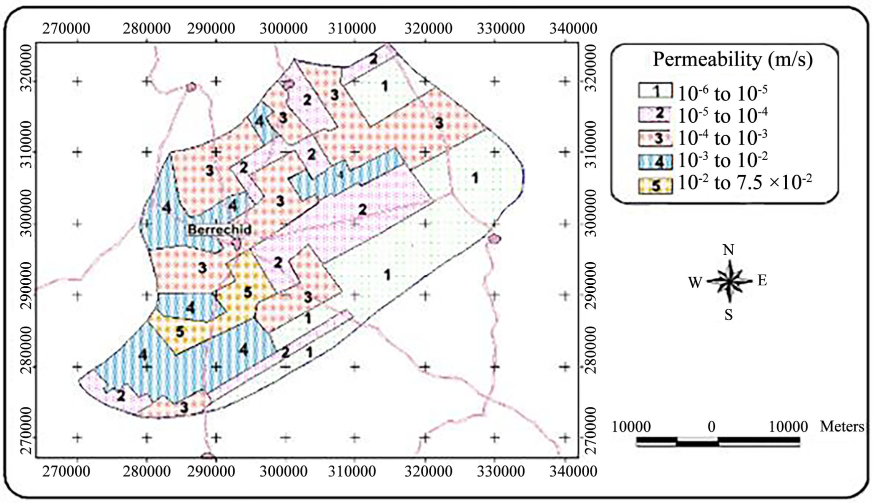

Figure 4. Distribution of the permeabilities resulting from steady-state calibration.

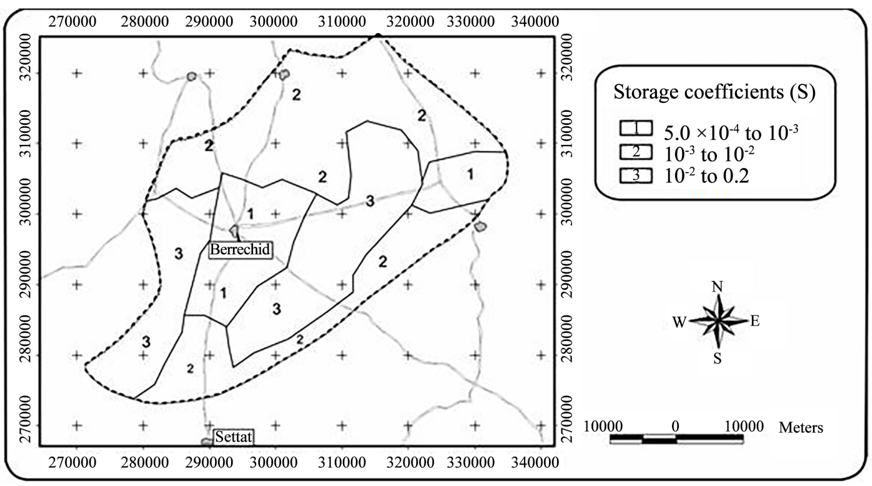

Figure 5. Distribution of storage coefficients from transient calibration.

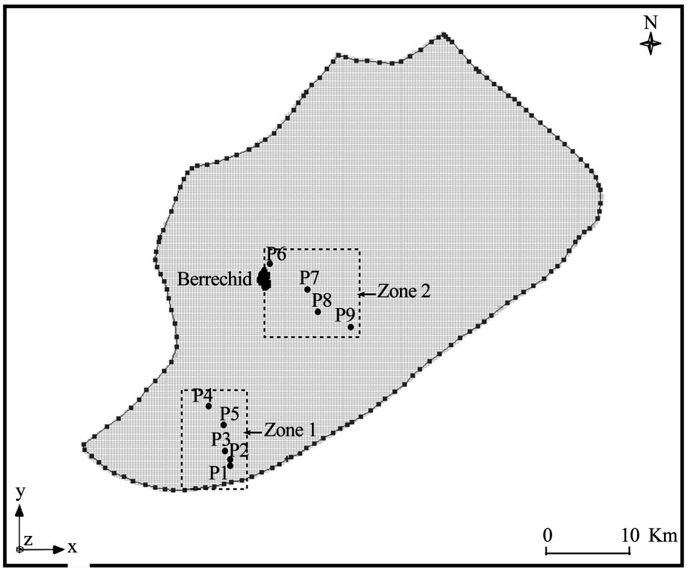

Figure 6. Major drinking water supplies the Berrechid nappe [10] [19].

Figure 7 and **Figure 8** show, respectively, the closed protective perimeters retracted from the drinking water supply wells located in zones 1 and 2 of **Figure 6**.

These perimeters, of elliptical shape, extend over variable surfaces. Within these perimeters, any bacteriological or chemical action is prohibited. The delimitation of protection perimeters has important consequences for the community, both in terms of health (protection and sustainability of the quality of the water produced) and economic (expropriations, costs of easements and protective works, constraints on land occupation). It is therefore necessary to have the possibility of optimizing the dimensions of the protection zones to minimize the constraints of the servitudes prevailing.

4.2. The Distant Protection Perimeter

Feeding areas have been introduced to protect groundwater from substances with insufficient degradation and natural retention. Indeed, the concepts of groundwater protection based on transit times, do not always prevent the arrival of these substances to capture. On the other hand, in the field of agriculture, good farming practices are not generally enough to sufficiently reduce the concentration of agricultural pollutants in groundwater. The purpose of these areas is therefore to define the most vulnerable sectors, with a view to applying protection actions as far as possible. These can be proposed for sanitation in already polluted waters, but also to prevent future contaminations. They are not determined on the basis of the flow of pollutant at a given moment, but on the circulation of water. These condition the transport of the majority of pollutants and have a lasting character over time, which makes it possible to propose long-term actions.

The MODPATH model also allows us to determine the feeding areas of water

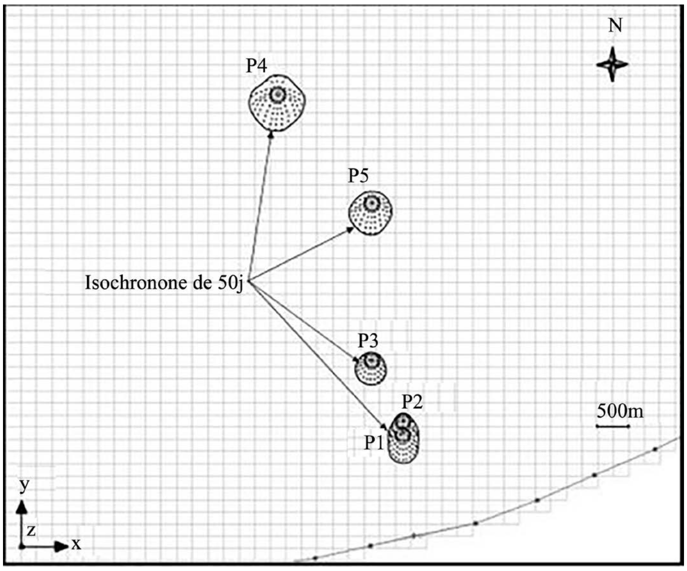

Figure 7. The closed protective perimeters of supply wells: 1951/27 (P1), 1950/27 (P2), 3061/27 (P3), 2024/27 (P4) and 1199/27 (P5).

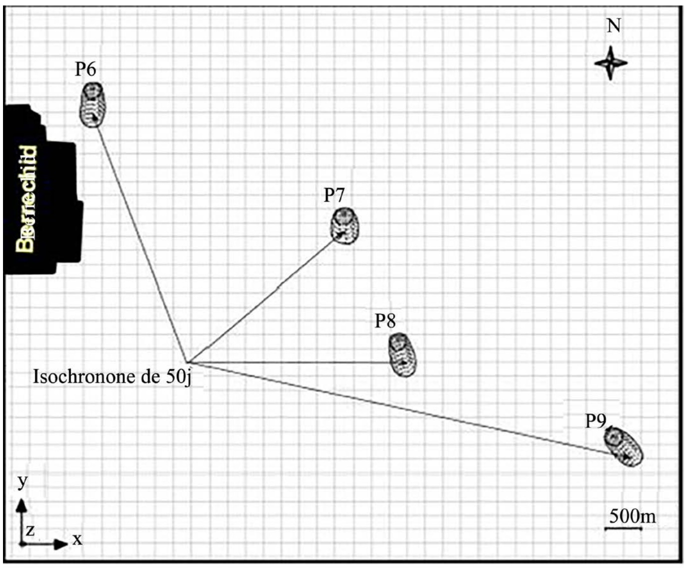

Figure 8. The closed protective perimeters of supply wells: 876/28 (P6), 3011/28 (P7), 1431/28 (P8) and 2149/28 (P9).

catchments (Figure 9). These areas correspond to the distant protection perimeters (infinite transfer time) that serve as an extension to the closed protection perimeters (transfer time of 50 days).

The area to be protected as a priority against pollution due to human activity is usually located upstream of the catchment and within a so-called capture (or catchment) area.

Figure 9 and Figure 10 show that these wells could be contaminated if the part of the southern water table, upstream of these wells, is polluted by persistent chemical substances. Thus, it would be useful to set up a pollution alert system in these vulnerable zones, the function of which would be to detect a contaminant at a sufficiently large distance from a well to allow an effective intervention. In practice, this warning network should consist of control piezometers where the quality of the water would be checked periodically.

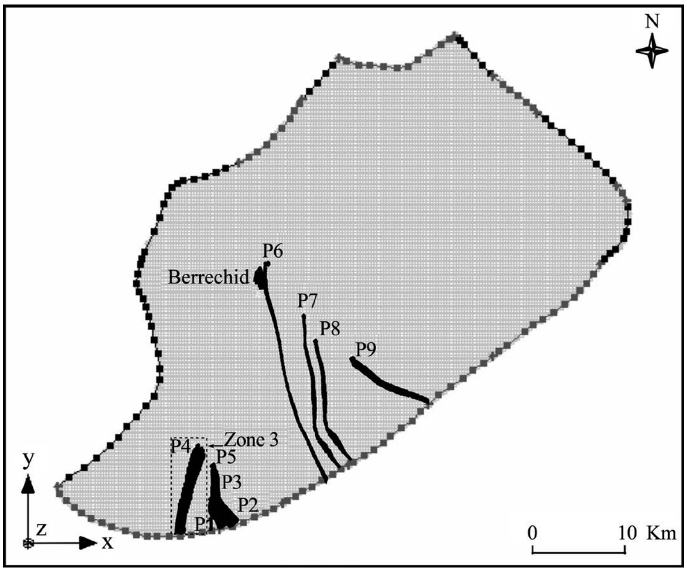

Figure 9. Path of water virtual particles captured by the boreholes and delimiting the protection zones.

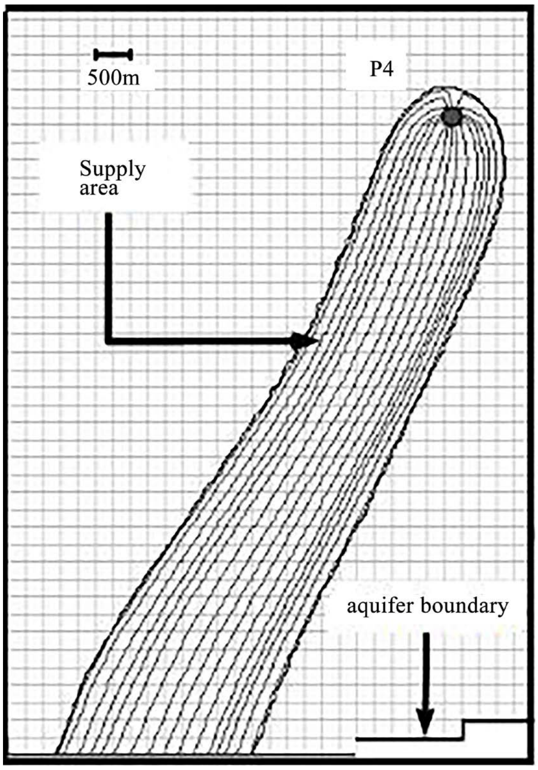

Figure 10. Enlarged view the feeding area of the borehole 1199/27 (P4).

5. Conclusions

The inherent risks in the pollution of a groundwater resource depend on the activities on the soil surface. In order to preserve its quality over the years, delimitation around perimeter collection of the boreholes, within which potential sources of contamination are managed and controlled, is essential.

The delimitation of distant protection perimeters has shown that drinking water wells could be contaminated if the part of the southern water table, upstream of these wells, is polluted by persistent chemical substances. A warning belt consisting of control piezometers seems essential to periodically check the quality of the groundwater upstream of the boreholes in the southern part of the aquifer. It is also imperative to limit the establishment of potentially polluting industrial units outside the developed sites and to speed up the implementation of catchment protection perimeters.

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