ANSES Opinion
Request No 2012-SA-0255

The General Directorate

Maisons-Alfort, 6 April 2016

OPINION
of the French Agency for Food, Environmental and Occupational Health & Safety

on the "health risks related to managed aquifer recharge"

ANSES undertakes independent and pluralistic scientific expert assessments.
ANSES's public health mission involves ensuring environmental, occupational and food safety as well as assessing the potential health risks they may entail.
It also contributes to the protection of the health and welfare of animals, the protection of plant health and the evaluation of the nutritional characteristics of food.

It provides the competent authorities with the necessary information concerning these risks as well as the requisite expertise and technical support for drafting legislative and statutory provisions and implementing risk management strategies (Article L.1313-1 of the French Public Health Code).

Its opinions are made public.
This opinion is a translation of the original French version. In the event of any discrepancy or ambiguity the French language text dated 6 April 2016 shall prevail.

ANSES issued an internal request on 27 November 2012 to carry out an expert appraisal on "Qualitative assessment of the health risks related to managed aquifer recharge".

1. BACKGROUND AND PURPOSE OF THE REQUEST

Groundwater is naturally recharged by rainwater, primarily in autumn and winter in mainland France. The water table fluctuates around a constant that can be affected in particular by anthropic activities. In France, more than 95% of catchment systems for the production of drinking water use groundwater and they produce 67% of tap water. For industry and the agricultural sectors, groundwater accounts for about 40% of water abstracted. Increased demographic pressure, which may be local and/or limited in time, heightens demands on groundwater resources. Simultaneously over the last few decades, the size of impermeable surfaces has increased while that of natural groundwater recharge areas has decreased. These changes have been accompanied by climate changes that in some regions have been characterised by recurrent episodes of water shortages, prompting local authorities to issue decisions restricting water abstraction.

Currently, management measures for groundwater resources encourage water savings, for example by adjusting groundwater abstraction to the natural recharge capacity of aquifers or by promoting natural recharge by retaining rainwater in the plot itself. However, these measures are

generally not adequate to address deficits in natural recharge, meaning that other solutions need to be found. Given this situation, managed aquifer recharge may help to fulfil various objectives, particularly quantitative but also qualitative maintenance of resources used for the production of drinking water or for agriculture. In advance, however, it is important to identify the hazards and health risks that may be associated with this practice.

Within this framework, measure 3.2 of the French National Climate Change Adaptation Plan (PNACC) stipulates that ANSES will specifically examine *"the establishment of prerequisites for water for infiltration or injection, with the aim of preserving the quality of water resources, in particular those used for production of drinking water."*

The French Environment Code, in Article R. 214-1, considers that managed aquifer recharge falls under the obligations related to class A of hydraulic infrastructure. This practice is part of category 14 "systems for catchment or managed aquifer", and is subject to authorisation.

Moreover, at the European level, the Water Framework Directive (WFD - 2000/60/EC), as amended, set the objective of good status for bodies of water for 2015, which for groundwater bodies requires a good quantitative and a good qualitative status. In 2013 in France, 90.4% of groundwater bodies had a good quantitative status while 67% had a good chemical status. The directive provides for the possibility of exemptions to the 2015 deadline to achieve good water status: Member States can request additional time (2021 or 2027 deadlines) or an easing of the objectives. Managed aquifer recharge is a possible alternative to achieve the qualitative or quantitative objectives of the WFD and is mentioned for this purpose in Annex VI of this directive.

This expert appraisal aims to establish recommendations to limit health risks related to managed aquifer recharge on the basis of the questions listed in the internal request. The following practices were not considered as managed aquifer recharge systems and were excluded from the scope of the expert appraisal:

- bank filtration which is not aimed at storing water in aquifers;
- infiltration of treated wastewater from wastewater treatment plants (WTPs) in the absence of a surface outflow, which is not intended to recharge groundwater but to eliminate treated wastewater;
- motorway infiltration basins for stormwater which are intended for elimination of stormwater and not recharge of groundwater.

2. ORGANISATION OF THE EXPERT APPRAISAL

The expert appraisal was carried out in accordance with French Standard NF X 50-110 "Quality in Expert Appraisals – General Requirements of Competence for Expert Appraisals (May 2003)".

The expert appraisal falls within the area of expertise of the Expert Committee (CES) on Water. ANSES tasked the Working Group (WG) on Qualitative assessment of the health risks related to managed aquifer recharge with the appraisal. The findings concerning both methodological and scientific aspects were presented to the CES between 6 May 2014 and 2 February 2016. They were adopted by the CES on Water during its meeting on 8 March 2016. The report issued by the WG takes into account the comments and additional information provided by the members of the CES. The results were therefore produced by a group of experts with complementary skills.

The appraisal is based on experience of managed aquifer recharge carried out in France and abroad, on scientific and institutional publications, and on hearings. As part of its work, the WG held hearings on 10 December 2013 with representatives from:

- the French Geological Survey (BRGM) ;
- the French Professional Federation of Water Companies (FP2E).

Information on experience concerning managed aquifer recharge carried out in France was collected on the basis of a questionnaire developed by the WG and intended for water agencies and ministries responsible for the environment and health that relayed the request to decentralised services charged with water management.

Members of the ENDWARE[1] European network (informal group in charge of drafting regulations on drinking water for Member States of the European Union) were contacted concerning their respective experience in managed aquifer recharge.

ANSES analyses the links of interest declared by the experts prior to their appointment and throughout the work, in order to avoid potential conflicts of interest with regard to the matters dealt with as part of the expert appraisal.

The experts' declarations of interests are made public via the ANSES website (www.anses.fr).

3. ANALYSIS AND CONCLUSIONS OF THE WG AND CES

The WG defined managed aquifer recharging as a practice involving artificial introduction of water into an aquifer in a deliberate controlled manner to increase its natural recharge.

To ensure clarity, the WG defined water at different stages of managed aquifer recharge:

- **raw recharge water**: water entering the managed aquifer recharge system from a variety of sources: surface water, wastewater, stormwater, and groundwater;
- **recharge water (water treated for recharge)**: water entering the managed aquifer recharge system (infiltration or injection) that has undergone treatment for artificial recharge;
- **native groundwater**: groundwater upstream of the managed aquifer recharge system and not affected by it;
- **recharged groundwater**: groundwater affected by the managed aquifer recharge system;
- **water abstracted after recharge**: groundwater collected downstream of the managed aquifer recharge system. This water is a mix of native groundwater and recharge water;
- **supply point water**: water from the aquifer that has been recharged and that can be treated or stored before being transported to the supply point.

3.1. International context

Managed aquifer recharge is particularly developed in countries under high water stress such as Australia, the United States, Israel, and South Africa. As a result, these countries have often regulated this practice based on principles of preserving water quality in the recharged aquifer, absence of additional treatment for the same use compared to a non-recharged resource, and sustainability of the system. Countries that authorise managed aquifer recharge with treated wastewater regulate these practices on a case-by-case basis and for a limited time, with infiltration standards being a part of the authorisation.

Figure 1 presents a diagram of the main managed artificial recharge practices in the world. They may differ depending on the country and the degree of water stress:

- stormwater is used as raw recharge water almost only in Australia;
- surface water is used as raw recharge water almost only in Europe;

[1] ENDWARE: European Network of Drinking-Water Regulators.

- recharging by injection is the preferred method in countries under high water stress;
- the aim of managed aquifer recharge is mainly quantitative in countries under high water stress while it is more qualitative in other cases;
- raw recharge water generally undergoes specific treatment before recharging.

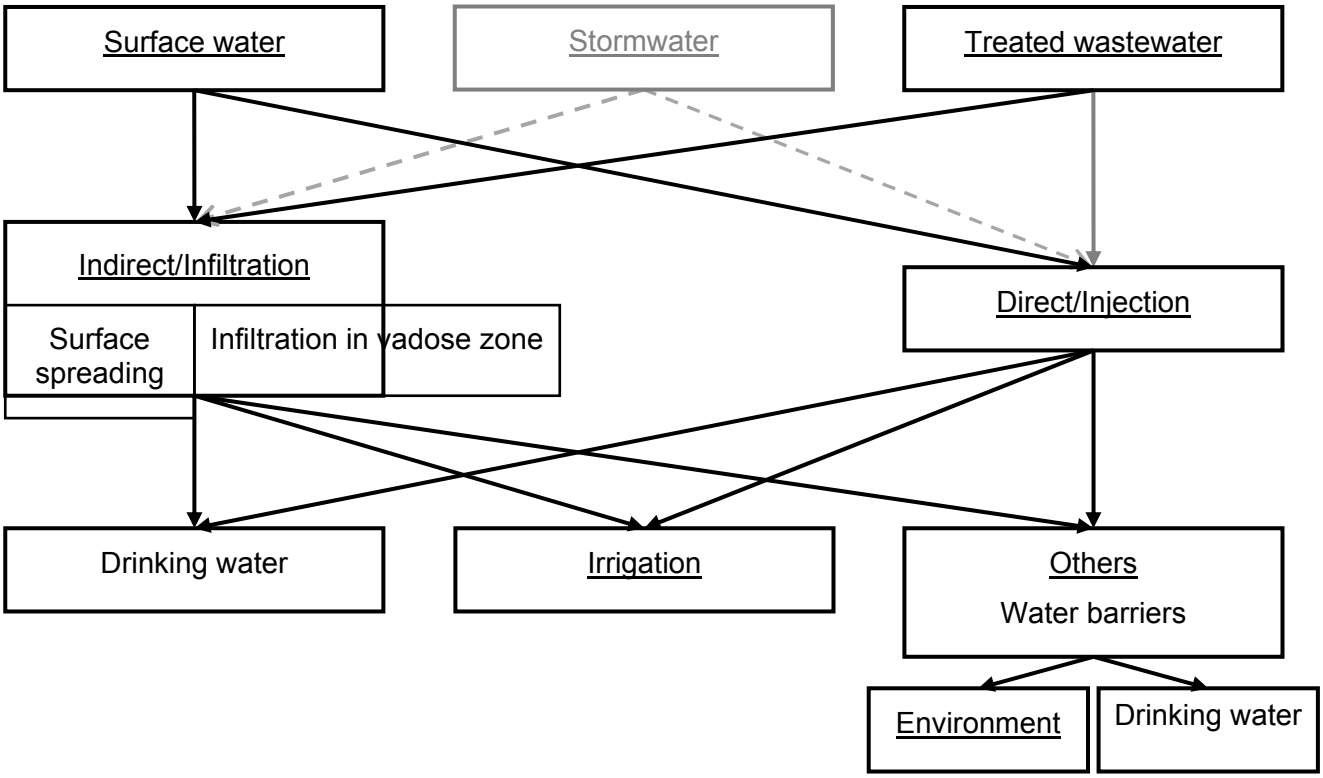

Figure 1. Practices for managed aquifer recharge worldwide.

3.2. Using managed aquifer recharge in France

Although France is not a country with high water stress, groundwater resources may locally and/or occasionally be insufficient. Urban development, seasonal influx of tourists and high demand for irrigation may increase this pressure. Climate change may also lead to an increase in deficient areas and longer periods of shortages that could affect water resources in certain parts of the country. Managed aquifer recharge could then be considered as a means of sustainably managing these resources and reaching the objectives of good quantitative status of groundwater.

Managed aquifer recharge can only be considered if geological strata have porosity consistent with storing sufficient volumes of water to constitute a reservoir and if the media is sufficiently permeable. If the aquifer is confined, the only possible solution is direct injection by drilling into the saturated zone. However, if the aquifer is unconfined, water can be injected into the saturated and/or vadose zones, or infiltrated through basins. Managed aquifer recharge by infiltration nonetheless requires a zone that has sufficient permeability to enable the recharge water to filter vertically into the aquifer. France's overseas departments and regions are a special case. Even though the demand for water can be high, the geological characteristics are generally not conducive to managed aquifer recharging. As a result, only mainland France was considered in this Opinion.

French law provides for managed aquifer recharge on a case-by-case basis subject to prefectural decision, bearing in mind that the water used can be taken from any source of surface water or groundwater provided that its use does not compromise environmental objectives for the recharged body of groundwater. Moreover, to prevent any pollution or deterioration in the quality of groundwater, French regulations require monitoring of the chemical and quantitative status of groundwater. In addition to the regulations concerning the general quality of groundwater, resources used for production of drinking water are subject to specific regulations regarding quality and that aim to ensure resource protection.

Managed aquifer recharge, as currently implemented in mainland France, mostly has quantitative objectives with seasonal increases in resources, and/or a qualitative objective to preserve water resources against pollution or saltwater intrusion. Raw recharge water mainly comes from watercourses. Recharging through groundwater is currently extremely limited. Recharging is usually done through infiltration basins, with recharging via injection being far less common.

Rainwater is not used in France as a source of raw recharge water, unlike in certain arid countries such as Australia. Since supply from this resource is irregular and variable from one year to the next, it is not possible to predict available volumes for recharge in the medium and long term. As a result, the WG did not consider the health risks related to recharging from this source of raw water in its assessment.

3.3 Raw recharge water considered suitable in France and their quality

For the purposes of this report, two types of raw recharge water were considered suitable in France: surface water, and in particular watercourses, and treated water. Both types of water often carry a wide range of microbiological and chemical contaminants.

The quality of surface water is highly variable and depends on the hydrological functioning of the resource, the activities on the watershed and the discharges in the area. A single resource can display major variations over time in terms of the available volume and quality. Surface resources are susceptible to authorised discharges and to spills in the event of defective treatment systems or accidents that may temporarily lead to a high concentration of contaminants. Surface water is highly influenced by effluents from domestic WTPs and urban areas. Most studies on the microbiological quality of surface water show significant variations in concentrations of pathogenic microorganisms which can be explained by the different sampling characteristics: place (proximity to discharges, uses of watersheds), seasons, and rainfall. Metals and trace elements found in aquatic environments may be of natural or anthropic origin. Barium, zinc, copper, boron, nickel, titanium and vanadium are often found in watercourses in mainland France. With regard to organic contaminants monitored in the context of the WFD, pesticides are found in 93% of water samples at monitoring stations along watercourses in the country and other organic micro-pollutants (of which 7/10 are polycyclic aromatic hydrocarbons) are detected at 86% of monitoring stations. The main results of an analysis campaign regarding emerging contaminants[2] showed a strong presence of pesticide metabolites, and even banned pesticides (quizalofop, omethoate), as well as personal care products, petrol additives and medicinal product residues, including non-steroidal anti-inflammatories and anxiolytics.

The quality of treated wastewater depends on the quality of the raw wastewater and how the water is treated. French regulations stipulate requirements for effluent from WTPs concerning monitoring parameters for carbon, nitrogen and phosphorus pollution. The main pathogenic microorganisms

[2] Botta F, Dulio V (2014) *Résultats de l'étude prospective 2012 sur les contaminants émergents dans les eaux de surface continentales de la métropole et des DOM* [Results of a prospective 2012 study of emerging contaminants in continental surface water in mainland France and overseas *départements*]. Ineris and Onema.

found in wastewater in mainland France are *Salmonella*, *Shigella*, *Campylobacter*, strains of enteropathogenic *Escherichia coli*, enteric viruses, *Cryptosporidium* spp. and *Giardia intestinalis*. The reduction rates observed during treatment depend on both the treatment process under consideration and the type of micro-organism. About half of the substances found in raw wastewater are eliminated at more than 70% in a standard biological system. However, a certain number of contaminants are eliminated at less than 30%: for example, pesticides or their polar transformation products (glyphosate, aminomethylphosphonic acid, diuron), certain medicinal product residues (carbamazepine, diclofenac, propranolol, sotalol) and carboxylates. Use of advanced treatment systems, including oxidation, adsorption or membrane processes, can help to reduce concentrations of microbiological and chemical contaminants in treated wastewater.

The quality of recharge water was studied for sites of managed aquifer recharge selected as examples for the report. Concentrations of microorganisms in the recharge water studied were often lower than those observed in raw water of the same origin in France (treated wastewater or surface water). Treatments applied to raw recharge water do not necessarily have an effect on the concentrations of chemical contaminants. For example, for metallic trace elements (MTEs) and for some organic chemical contaminants (carbamazepine and sulfamethoxazole), concentrations in recharge water at certain sites are comparable to those described in wastewater treated by activated sludge in France. Lastly, when advanced treatments are applied to raw water before recharge, like in Wulpen, Belgium, with a reverse osmosis step, this water has very low levels of microbiological and chemical contamination.

3.3. Technical aspects of managed aquifer recharge

Managed aquifer recharge can be carried out through two main approaches: recharge by infiltration through the vadose zone, and recharge by direct injection into the aquifer. Irrespective of the approach, recharge water must have low quantities of total suspended solids (TSS) and organic matter to reduce the technical risk of clogging the layer. In view of the literature data, the WG considers that recharge water must comply at least with the following limits:

- TSS: < 10 $mg.L^{-1}$;
- Turbidity: < 5 FNU;
- Total organic carbon (TOC): < 10 $mg.L^{-1}$.

Higher water quality may be necessary, particularly for recharging by injection. As a result, raw recharge water undergoes prior treatment. For surface water, this treatment generally includes at least one decantation.

In order to prevent degradation of recharged groundwater quality and any hydraulic disturbance or geotechnical issue, the composition of the recharge water must be compatible with the materials composing the aquifer. The main parameters to take into account are temperature, pH, redox potential, and ion concentrations. Concerning hydraulic issues, scale-forming water may reduce the porosity and permeability of the aquifer and thus impair groundwater underflow. However, aggressive water may dissolve the aquifer formation if the rock is soluble, and thus compromise its stability or threaten the integrity of the impermeable separating layers.

Although many managed aquifer recharge projects consider mixing of recharge water with native groundwater, this mixing is not systematic. This is because certain sites do not enable rapid homogenisation of water. In addition, due to a difference in water density, use of managed aquifer recharge to create a water barrier intended to prevent intrusion by the saltwater wedge in coastal aquifers does not result in a consistent mixing of infiltrated water with groundwater. The freshwater forms a low-density water mass floating on the brackish water. Therefore, the concentrations of contaminants in the recharged groundwater do not necessarily result from a proportional

intermediary balance between the concentrations in the recharge water and those in the native groundwater.

The attenuation in concentrations of contaminants on transfer to the vadose zone or to the aquifer depends on the type of contaminants and type of aquifer.

- The microorganisms may be inactivated or adsorbed. Persistence depends specifically on the type of microorganism, the type of aquifer, geochemical conditions, transfer time and native microfauna in the aquifer.
- Metallic trace elements can be displaced from the liquid phase to solid surfaces (adsorption, complexation or precipitation), absorbed by living organisms or displaced from the surface inward to the solid phases. Their distribution between the various ground compartments is determined by their speciation, which can itself change depending on geochemical conditions. The oxidizing or reducting nature of the recharge water determines the forms of elements in solution, for example arsenic which is solubilised when the medium is oxidant.
- The main routes of organic micropollutant attenuation are sorption and biodegradation; biodegradation generally results in creation of transformation products.

Since the geochemical conditions in the aquifer may be altered during recharge, contaminants that were initially adsorbed or complexed may be desorbed and released into to the groundwater. The contaminants may be present naturally in the aquifer (geochemical background) or originate from prior contamination of the site. Moreover, during managed aquifer recharge, a contaminant may adsorb for a certain amount of time and then desorb. Given the major differences between managed aquifer recharge sites and the wide range of contaminant behaviours, it is not possible to determine standard reduction rates, by class of contaminants, applicable to all managed aquifer recharge sites.

Modelling can help to better understand the behaviour of chemical contaminants in the aquifer, provided that they are first adjusted to the studied site. A single model cannot be used for all chemical contaminants or for all processes involved in the fate of these contaminants in the aquifer. As such, although they can be considered an additional tool in monitoring the chemical quality of groundwater, models do not currently enable us to dispense with measurement programmes for the water in recharged aquifers.

Lastly, use of markers may assist in spatially visualising the preferential flow of recharge water in the aquifer and in assessing the effect of recharge water on the quality of the groundwater. Selecting markers is a critical step that must take into account the origin and quality of the recharge water, as well as the characteristics of the recharged aquifer. Although markers are useful in characterising a recharge site and in monitoring changes in the quality of recharged groundwater, the WG considered that given the current level of knowledge, it is not possible to put forward standard markers for all managed aquifer recharge sites in France. However, the WG does believe it necessary to continue research in order to be able to propose markers that can monitor the transit of water during managed aquifer recharge and the impact of recharge on the quality of recharged groundwater.

3.4. Identification of hazards to humans related to managed aquifer recharge

Data on the contaminants present in water abstracted after managed aquifer recharge groundwater are sparse and are insufficient to identify all the relevant hazards from a health perspective for all the recharge sites.

During managed aquifer recharge, pathogenic microorganisms come mainly from the recharge water. The microorganisms of public health interest are those that persist during treatment of

recharge water, during percolation in the vadose zone and the aquifer. On the basis of the available studies, enteric viruses, *Giardia* cysts and *Cryptosporidium* oocysts are considered to be the pathogens that persist to the greatest extent in these circumstances. Given the lack of available data on contamination of groundwater in France by viruses and difficulties related to these analyses (cost, comparability of methods, infectivity of the quantified viruses), it is premature to recommend monitoring of viruses at managed aquifer recharge sites in France.

In water abstracted after recharge, metallic trace elements may originate from recharge water, native groundwater, and/or from interactions of recharge water with the aquifer. Current treatment techniques enable reduction of metallic trace element concentrations in recharge water. However, metallic trace elements originating from the aquifer are the most difficult to assess during managed aquifer recharge and require evaluation of the compatibility between recharge water and the aquifer in terms of pH and redox potential.

Organic chemical contaminants in water abstracted after recharge may originate from raw recharge water or result from transformation during treatment of recharge water or during transfer into the aquifer. Given the wide variety of organic chemical contaminants that may be present in water abstracted after recharge, it is not possible to identify the most relevant contaminants to consider for all the managed aquifer recharge sites in France. Some contaminants that are more persistent are often found at measurable concentrations in recharged groundwater and in water abstracted after recharge. For example, this is the case for disinfection by-products or emerging contaminants such as carbamazepine, sulfamethoxazole and benzotriazole.

In order to manage the health risks related to managed aquifer recharge, two approaches are adopted. The first involves the establishment of general constraints concerning the quality of raw water and recharge water, the treatment of recharge water, and the design of recharge sites. This is the approach adopted in the Californian regulations and by the US Environmental Protection Agency (EPA). The second approach involves applying a quality management scheme at each recharge site, like the approach for Hazard Analysis Critical Control Points (HACCPs) or the system proposed in Australian guidelines.

The CES adopted the following position:

- compared to a non-recharged resource, water abstracted from managed aquifer recharged sources must not require additional treatment for the same use;
- all recharged groundwater must be compatible with their current or future use to supply drinking water in order to avoid undermining these resources for the future;
- the aquifer but also the vadose zone are compartments that must be protected; therefore, recharge water must not lead to their degradation;
- reductions that may occur in these compartments have not been taken into account to formulate the recommendations on managed aquifer recharge: the constraints thus concern the quality of the recharge water.

3.5. Recommendations

Managed aquifer recharge must not undermine the quality of groundwater nor require additional treatments after abstraction for the same use with respect to a non-recharged resource. It must not compromise environmental objectives defined for underground water bodies influenced by managed aquifer recharge, which includes preservation of connected terrestrial ecosystems. The quality of recharge water must therefore be better or at least equivalent to the quality of the groundwater and managed aquifer recharge must not disrupt the hydrogeochemical balance of the recharged aquifers in order to limit potential release of contaminants originally stored in the

subsurface environment. In addition, the managed aquifer recharge system implemented must be sustainable.

Projects for managed aquifer recharge must be based on a specific need related to the target water resource (qualitative and/or quantitative), and not offset losses of the supply network, nor be intended solely to eliminate treated wastewater.

Among the various recommendations, the most stringent applies as a priority.

3.5.1. Regulations

3.5.1.1. Regulations concerning managed aquifer recharge

Currently, French regulations enable managed aquifer recharge on a case-by-case basis, following prefectural authorisation and specifying that the water used can originate from any surface or groundwater provided that its use does not compromise attainment of environmental objectives concerning recharged or augmented underground bodies of water. Application dossiers for prefectural authorisation must include an impact assessment that requires the intervention of a hydrogeologist accredited in terms of public hygiene.

3.5.1.2. Regulations concerning groundwater

Once recharge water enters the underground environment, it becomes groundwater. Monitoring controls of the chemical status of groundwater then become applicable. It requires monitoring of many parameters, primarily concerning micropolluants. Managed aquifer recharge must be incorporated into plans known as SDAGE[3] and SAGE[4] and must not impede environmental objectives for recharged resources.

3.5.1.3. Siting of managed aquifer recharge systems and catchment protection zones for the production of drinking water

When aquifers are artificially recharged to cover additional needs for drinking water, the recharge site will inevitably be located in the drainage area of the catchment or catchments using the aquifer, and may therefore also be located in the catchment protection zones depending on their sizes.

Protection zones are intended to preserve the quality of the water abstracted from the catchment by acting on the activities present or that may develop in the drainage area of the catchments. As a result, the quality of the recharge water must not be lower than that of the aquifer. For catchments under derogation, recharge water must be of better quality than the recharged water, particularly for the parameter(s) downgrading the status of the groundwater body under consideration.

The objective of excluding development of activity in the immediate protection zone, and the small size of the area (in hundreds of m^2 generally) in principle rules out siting of an managed aquifer recharge system in this type of location. This is because a recharge site requires maintenance and access for vehicles to run the system. Moreover, not siting the recharge system within the immediate protection zone helps to increase the transfer time of recharge water into the aquifer before abstraction for supply of drinking water. This thereby adds another level of protection for the consumer. As a result, installing a recharge system in the immediate protection zone is not workable.

Recharging systems may be sited in the inner or outer protection zones, bearing in mind that the quality of the infiltrated water must not affect that of the water abstracted from the catchment. The Order of declaration of public utility must be amended accordingly.

[3] SDAGE: Master plan for water management and development
[4] SAGE: Plan for water management and development

3.5.2. Designing managed aquifer recharge projects

3.5.2.1. General description of the site

Before considering a groundwater recharge project, it is important to assess the current and future water needs of the given community and to include this project in the relevant plans for water management and development (SDAGE and SAGE, as appropriate). The impact of surface water withdrawal on surface hydrology or the decrease in discharge from WTPs related to an managed aquifer recharge project must be evaluated, particularly in the event of transfers of water bodies between watersheds. Alternatives to groundwater recharge should be studied beforehand. The catchments for the aquifer for which the managed aquifer recharge is under consideration must be identified and all the uses of this aquifer recorded.

In addition, the managed aquifer recharge site must be properly characterised. To do this, it is necessary to describe at least:

- the characteristics of the aquifer: size, type of rock, confined or unconfined aquifer;
- the porosity, storage, permeability and thickness of the vadose zone, if relevant,
- the pressures the recharge water is subject to (diffuse pollution, discharge from urban WTPs, industrial discharges);
- the uses of the aquifer and water needs;
- and any other relevant element to describe the selected site.

3.5.2.2. Choice of the recharge method

In addition to technical and economic considerations, the choice of the managed aquifer recharge method must also consider the fact that stagnant water, for instance in infiltration basins, can promote proliferation of certain insect vectors (potential larval habitats) and thus increase the risk of transmission of vector-borne diseases.

Once the decision to implement a recharge project has been made, and once the recharge system has been selected, along with the source of recharge water, an in-depth study of the aquifer is needed. It must examine hydrogeology and composition of the aquifer.

3.5.2.3. Understanding the functioning of the aquifer to be recharged

To understand the hydrological functioning of the aquifer during recharge, it is necessary to determine, as a minimum, by tracing and modelling:

- its diffusivity;
- the type of underflow of recharge water in the aquifer;
- the type of mixing of the recharge water in the aquifer;
- the ratio of the infiltrated volume to the volume of the aquifer and thus the transfer time of recharged water in the aquifer.

3.5.2.4. Compatibility between recharge water and recharge site

To assess the compatibility of the recharge water with the recharge site, the following parameters, as a minimum, must be measured in the raw recharge water, the recharge water, and the native groundwater:

- conductivity;
- pH;
- calcium-carbon balance;
- redox potential (depending on the type of aquifer);

- ion concentrations;
- and any other relevant information for the selected site.

In addition, the geochemical background of the recharge site must be characterised.

Using a geochemical model may make it possible to estimate the range of values of the recharge water parameters that do not significantly alter the physico-chemical balance established in the aquifer before managed aquifer recharge.

3.5.2.5. Protection of the recharge site

Since the site is a water entry point into an aquifer used for drinking water, the recharge site must be protected even if the water transfer time to the point of abstraction is generally long. This would involve satellite perimeters, like those created around a sinkhole to protect catchments supplied by a karst aquifer.

Depending on the type of system and its ground footprint, and especially the need to intervene on recharge infrastructure, this could be an immediate protection zone for injection drilling, but more commonly an inner protection zone, particularly for infiltration systems using basins. The multiple maintenance operations on basins rule out the use of an immediate protection zone for infiltration systems using basins.

3.5.3. Quality of the recharge water

As mentioned in section 3.4, the WG focused on drinking water use to establish health requirements for managed aquifer recharge. The recommendations apply to managed aquifer recharge systems using both infiltration and injection.

3.5.3.1. Treatment of raw recharge water

Raw recharge water for managed aquifer recharge must undergo prior treatment. Treated wastewater used must comply with regulations concerning sanitation facilities[5].

3.5.3.2. Monitoring of the recharge system

In order to avoid possible variations in the quality of raw water entering the groundwater recharge system and to ensure proper functioning of treatment facilities, the following parameters must be monitored continually in recharge water:

- pH,
- conductivity,
- turbidity,
- redox potential.

3.5.3.3. Quality of recharge water

For recharge water, the CES on Water recommends, irrespective of the resource for raw recharge water:

- quality at least equivalent to that of the native groundwater for the parameters in Annex II[6] of the Order of 11 January 2007 regarding reference limits for the quality of raw water and

[5] Order of 27 July 2015 amending the Order of 25 January 2010 regarding the methods and evaluation criteria for the ecological status, chemical status, and ecological potential of surface waters in application of Articles R. 212-10, R. 212-11 and R. 212-18 of the French Environment Code.

[6] Quality limits for raw water of any origin used for the production of WIHC, excluding bottled spring water, established in application of the provisions of Articles R 1321-7 (II) and R1321-42.

water intended for human consumption (drinking water) mentioned in Articles R. 1321-2, R. 1321-3, R. 1321-7 and R. 1321-38 of the Public Health Code, and compliance with limits for the quality of raw water of any origin used for the production of drinking water;

- non-detection of *Cryptosporidium* oocysts and *Giardia* cysts;
- a monitoring frequency of once a month for the duration of the site's operation.

3.5.4. Monitoring of the recharge site

To ensure that the quality of the recharged groundwater is not degraded and that contaminants that could present a health risk at the supply point do not accumulate, it is necessary to ensure regular monitoring of the quality of the aquifer. Monitoring should cover:

- recharge water,
- recharged groundwater,
- native groundwater.

In addition, to have data for comparison, an overview of the aquifer quality must be prepared before commissioning of the recharge system.

If abnormal concentrations are observed in recharged groundwater related to recharge practices, recharge must be suspended pending implementation of suitable corrective measures.

3.5.4.1. Parameters to monitor

- Use of water tracers

In addition to continual monitoring of the aquifer, water tracers must make it possible to determine the proportion of recharge water in the aquifer. These tracers are not specific to each site; chlorides may be suitable tracers for bodies of water.

- Chemical contaminants

In order to ensure that the quality of the aquifer is not affected, the WG recommends monitoring of all control parameters of the chemical status of groundwater mentioned in the Order of 7 August 2015 amending the Order of 25 January 2010 establishing the monitoring programme for the status of water in application of Article R. 212-22 of the French Environment Code. This monitoring can be supplemented by any relevant parameters for the given managed aquifer recharge site that may be required for instance because of high occurrence in the raw recharge water, a high local geochemical background, or treatments applied to recharge water (disinfection by-products).

3.5.4.2. Monitoring system

- Siting of sampling for monitoring of groundwater

To monitor the quality of groundwater, it is necessary to implement sampling systems (piezometers and quality meters) upstream and downstream of the recharge site. The number and location of these sampling devices will be determined based on:

- the water transfer time, which depends on transmissivity of the aquifer and the hydraulic gradient; the faster the underflow, the greater the required network density;
- the homogeneity of the aquifer: aquifers with fractured bedrock or karsts require a denser monitoring network than intergranular aquifers, including alluvial aquifers.

A homogenous media and a transfer time of several months between the recharge system and the abstraction drilling site will only require a sampling well located a few dozen metres upstream of the recharge system, and another downstream well located between the two installations.

In the case of aquifers with varying underflow velocities and/or that are more or less channelised, additional wells should be placed downstream of the recharge system to ensure the representativeness of the entire water system affected by recharge.

- Conditions of sampling and analysis

The conditions of sampling and analysis to implement are those described in the Order of 7 August 2015 amending the Order of 25 January 2010 establishing the monitoring programme for the status of water in application of Article R. 212-22 of the French Environment Code.

- Frequency of analysis

The frequency of controls to be implemented is two per year (one sample during the high-water period and one during the low-water period) and the number of years of monitoring by SDAGE is identical to that established in Table 49a of the Order of 7 August 2015 cited above.

3.5.5. Quality of the water abstracted after recharge

Given the additional pressure that managed aquifer recharge places on water resources, in the event of use of a catchment for the production of drinking water, the frequency of sampling and analysis of water in the framework of health assessment must be increased:

- for the resource, to 12 analyses of the RP[7] type per year, i.e. one per month for the duration of operation of the site and then depending of the transfer time in the aquifer;
- for treated water, however, if it has been demonstrated that the treatment scheme enables compliance with the quality limits for drinking water[8] for the recharged resource, it is not necessary to adjust the frequency of health controls.

3.5.6. Research recommendations

3.5.6.1. Collection of data on managed aquifer recharge sites in France

To carry out further studies on the identification of hazards related to managed aquifer recharge in France, it is necessary to collect data generated through monitoring of the quality of recharge water, recharged groundwater, and water abstracted after recharge from sites in the country where groundwater has been recharged artificially.

3.5.6.2. Collection of data on microorganisms

Studies are needed to characterise microbiological contamination, particularly viral contamination, of groundwater in France and to put forward indicators for this contamination.

3.5.6.3. Collection of data on metallic trace elements

Simulation of hydrogeochemical models of addition of reverse osmosis water in the various types of aquifers found in France and used for drinking water would make it possible to predict the geochemical behaviour of facilities for managed aquifer recharge.

3.5.6.4. Collection of data on organic chemical contaminants

The CES on Water considers it necessary to continue research studies to propose tracers to assess the transit of water during managed aquifer recharge and the impact of recharge on quality

[7] Order of 11 January 2007 as amended, regarding the programme for sampling and analysis of health controls on water supplied by the distribution network, in application of Articles R. 1321-10, R. 1321-15 and R. 1321-16 of the French Public Health Code.

[8] Order of 11 January 2007 regarding the limits and quality references for raw water and WIHC mentioned in Articles R. 1321-2, R. 1321-3, R. 1321-7 and R. 1321-38 of the French Public Health Code.

of recharged groundwater. These studies could be based on results of monitoring of managed aquifer recharge sites operating in France. Moreover, strict monitoring of "pilot" sites for managed aquifer recharge could help to gain more knowledge on the fate (degradation, sorption, desorption) of organic chemical contaminants in the vadose zone in order to consider eventually including organic contaminants in predictive models.

3.5.6.5. Collection of data on hydrology during recharge

It would be useful to characterise physically and chemically the clogging processes and changes in porosity of an aquifer subject to injection or infiltration of slightly turbid water.

4. CONCLUSIONS AND RECOMMENDATIONS OF THE AGENCY

The French Agency for Food, Environmental and Occupational Health & Safety endorses the conclusions of the CES on Water.

Projections on the future of water resources related to climate change appear to indicate a probable decrease in groundwater resources in France in the future, associated with a decrease in natural recharge and possible rising of the saltwater wedge. As a result, measures to preserve water resources need to be taken. For example, in 2012 the European Commission launched an action plan for the protection of water resources in Europe that aims to encourage reuse of water. Managed aquifer recharge using surface waters or treated wastewater appears to be one of the solutions that could be used to mitigate the decrease in groundwater resources. However, ANSES emphasises the importance of preserving the quality of groundwater resources in the long term, specifically to guarantee quality compatible with production of drinking water, without needing to use additional treatments funded by local authorities and consumers.

In addition, ANSES considers it necessary to improve knowledge on sites of managed aquifer recharge in France, on the one hand to ensure sustained quality of recharged groundwater, and on the other to better characterise the hazards to humans mentioned in this Opinion. To this end, data on monitoring of the quality of recharge water, native groundwater, recharged groundwater, water abstracted after recharge, and supply point water need to be collected and made available.

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KEY WORDS

Managed aquifer recharge – health risks – infiltration of groundwater – injection of groundwater