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RESEARCH ARTICLE

Payment for environmental services related to aquifers: a review of specific issues and existing programmes

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Abstract
In Europe, payment for environmental services is increasingly perceived as an alternative to government-led incentives for promoting pro-environmental land use and attaining policy objectives of groundwater quality and quantity. The processes linking land-use decisions and ecosystem services related to aquifers (EcSA) are complex, involving different time and space scales. This raises specific challenges for the effectiveness of payment for environmental services related to aquifers (PEvSA). After defining the concepts of PEvSA, we highlight these challenges—uncertain links between land use and EcSA, spatial and temporal dimensions, monitoring and compliance issues, the invisibility of aquifers and the social equity/efficiency dilemma—and identify good practice and innovative designs for addressing them. We then review how existing PEvSA schemes throughout the world have succeeded, or not, in addressing these challenges and identify evidence of their effectiveness. We conclude that future implementation of PEvSA should pursue (i) the use of science-based approaches for determining land-use prescription; (ii) the adoption of result-oriented payments adapted to PEvSA; (iii) the use of longer term contracts adapted to water transfer time in aquifers; (iv) a finer spatial targeting of PEvSA; (v) the use of contracts with collective conditionality; and (vi) the labelling of products that generate EcSA as ways for stimulating demand. We finally call for establishing formal evidence of the impact of PEvSA on EcSA.

Keywords Payments for environmental services · Ecosystem services; Aquifer · Groundwater

Introduction

In Europe, payment for environmental services (PES) is increasingly promoted as a new silver bullet for tackling the shortcomings of existing policy instruments that promote pro-environmental land use. In 2015, in its '*Roadmap to a Resource*

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Efficient Europe', the European Commission highlighted PES as the first innovative market-based instrument for addressing the degradation of ecosystems. The concept of PES was also strongly present in the debates of the post-2020 Common Agricultural Policy (CAP) reform[1]. In France, too, the national biodiversity plan of 2018 secured 150 M€ for improving water quality and biodiversity through PES programmes. PES is thus perceived as a potentially 'new' policy instrument for addressing several environmental objectives, including groundwater protection.

The restoration of groundwater quality and quantity is a major target of European policies. The Water Framework Directive (WFD) and the Directive on Groundwater Protection aim at achieving good groundwater status and preventing significant damage to terrestrial ecosystems that directly depend on groundwater bodies (Kløve et al., 2011). The CAP, one of the major European programmes for achieving WFD objectives, has dedicated €80 billion in the 2014–2020 programme, targeting beneficial practices for the environment, of which water-quality protection is a prime objective (EEIG Alliance Environment, 2019). In 2018, however, 26% of groundwater bodies still did not respect the good chemical status criteria and 11% did not achieve a good quantitative status. Agri-environmental measures (AEMs), one of the major policy instruments of the CAP, have been criticized for many reasons, including their lack of flexibility, especially in terms of payment levels and their lack of effectiveness, due *inter alia* to their focus on action-oriented contracts (Kleijn et al., 2006; Matzdorf & Lorenz, 2010). PES, conceived as a voluntary transaction between service users and service providers that is conditional on agreed rules of natural-resource management (Wunder, 2015), are considered a promising alternative policy instrument. They notably are more flexible (Engel et al., 2008), as contract terms are negotiated between contracting parties rather than fixed by governments, and include result-based rather than action-based payments (Matzdorf & Lorenz, 2010), potentially guaranteeing higher effectiveness than pre-existing policy instruments. In this paper, we will try to verify whether this promise can be fulfilled.

The identification of issues affecting the effectiveness of PES and the design of innovative PES contracts for addressing these issues has been the subject of a flourishing literature (e.g. Calvet et al., 2017; Chabé-Ferret and Subervie, 2013; Engel et al., 2008; Ferraro, 2008; Kuhfuss et al., 2015). The specific question of the effectiveness of PES for improving ecosystem services related to aquifers has, however, not been addressed as far as we know. Yet, the processes linking land-use decisions and ecosystem services related to aquifers are complex, involving different time and space scales. This raises specific challenges for the effectiveness of payment for environmental services related to aquifers (PEvSA). The aim of this paper thus is to make recommendations for increasing the effectiveness of PEvSA, based on specific aquifer properties.

After clarifying the definitions and concepts associated with PEvSA, we identify issues that may create challenges for PEvSA implementation. We then discuss how they could be addressed, mainly by adapting existing recommendations for

[1] https://www.agriculture-strategies.eu/en/2018/09/will-the-payment-for-environmental-services-concept-cause-further-damage-to-the-environmental-side-of-the-cap/

improving the effectiveness of PES. The third section reviews existing PEvSA programmes, how they have handled (or not) these issues, as well as evidence concerning their effectiveness. The fourth section makes recommendations for the future rollout of PEvSA programmes.

Definitions and concepts

PES and PEvSA

The definition of payment for environmental services has raised various debates in the literature. The initial definition was by Wunder (2005): '*A voluntary transaction where a well-defined service (or land-use likely to secure that service) is being* "*bought*" *by a* (*minimum one*) *ES buyer from a* (*minimum one*) *provider if and only if the ES provider secures ES provision* (*conditionality*)'. Since then, at least eight alternative definitions have been proposed (see Wunder, 2015; Martin-Ortega and Waylen, 2018 for a review). Here, we adopt a simplified version of the revised definition proposed by Wunder in 2015: *Payments for Environmental Services* (*PES*) *can be defined as:* (1) *voluntary transaction* (2) *between service users* (3) *and service providers* (4) *that are conditional on agreed rules of natural-resource management.*

Some confusion also lies within the term itself, which is 'Payment for Ecosystem Services' in some articles (Kaczan et al., 2013; Martin-Ortega et al., 2013; Zanella et al., 2014; Martin-Ortega and Waylen, 2018) and 'Payment for Environmental Services' in others (e.g. Engel et al., 2008; Karsenty et al., 2017; Muradian et al., 2010; Wunder, 2015; Wunder et al., 2018). Here, we deliberately use the term payment for environmental services (PEvS)[2], considering that land users are paid for environmental services—land-use or -management decisions that contribute to maintaining or restoring ecosystem services (CGDD, 2017)—and not for ecosystem services that are by definition produced by ecosystems. The term PEvSA is used for those that aim at maintaining or restoring Ecosystem Services related to Aquifers (EcSA).

Although our aim was not to provide a new definition of PES, we emphasize key concepts pertaining to PEvS that we consider fundamental for identifying PEvSA. *Voluntariness* is one of the key aspects of PEvS (Martin-Ortega & Waylen, 2018; Wunder, 2005, 2015). In PEvSA, the providers voluntarily accept to enter or not in a transaction. However, depending on the context, service users may enter voluntarily in a transaction or be constrained to act due to the regulatory context. We also emphasize that the *conditionality* of payment to the environmental service provision—i.e. land users are paid if, and only if, they secure EvSA provision—is a key aspiration of PES, although this condition can be challenged in certain settings (cf. 'Review of PEvSA programmes' section, hereafter). We finally acknowledge the *large definition of EcSA users and EvSA providers* who may 'act individually or

[2] We deliberately use the acronym PEvS for designating Payment for Environmental Services; to avoid confusion with Payment for Ecosystem Services. We use EcS for Ecosystem Services and EvS for Environmental services.

collectively',[…] 'with government as the highest level of user aggregation' (Wunder, 2015). For this reason, we include government-led PEvSA in our analysis.

Ecosystem services related to aquifers and environmental services related to aquifers

We apply in this paper the conceptualization of ecosystem services related to aquifers as presented by Hérivaux and Maréchal (2019). Aquifers generate three main types of ecosystem services: (i) storage and supply of good-quality water; (ii) supply of water to ecosystems related to aquifers (wetlands, rivers and lakes); and (iii) flood regulation. The supply of (i) and (ii) largely depends on the quality and quantity of water available in aquifers, itself dependent upon parameters largely influenced by human action, such as the quality and quantity of water recharged into the aquifer, and the amount of water abstracted from the aquifer. For example, low-flow of rivers and river-water temperature are generally directly determined by aquifer levels. Wetland water levels are also largely connected to aquifer levels and are thus directly affected in case of over-pumping (WWAP, 2015).

We adopt the definition of environmental services developed in the French Evaluation of Ecosystems and Ecosystem Services (CGDD, 2017): those human actions that improve the state of ecosystems for the profit of other beneficiaries. Consequently, environmental services related to aquifers (EvSA) are those that improve the production of ecosystem services related to aquifers (EcSA). Here, we focus on environmental services that may fall within the scope of PES programmes. These include actions that are broadly related to land use, such as the modification of land cover (crop diversity, forest cover, etc.) and land-use practices (irrigation, use of inputs, etc.). We summarize these types of actions under the term land use decisions (LUD), which includes actors susceptible to carry out such actions as land users. LUDs are indeed estimated to be a major driver of groundwater recharge and groundwater quality (Scanlon et al., 2005). We distinguish three main type of environmental services:

- *Environmental services for protecting upstream ecosystems*. This mainly relates to LUDs that generate a positive impact on EcSA. Examples are the conservation/creation of forest cover or natural areas, to preserve the quality of water recharging aquifers, or the use of agricultural systems (crop types and agricultural practices) that lead to a reduction of pesticides and nutrient loads flowing into aquifers. Managed aquifer recharge can also be considered an environmental service of protection of an upstream catchment as it increases the availability of water in aquifers. In this case, land users, through the use of specific practices, such as the flooding of fields, generate an increase of aquifer recharge (Taniguchi et al., 2019).
- *Environmental services of sustainable groundwater management*. These may include support for the adoption of irrigation practices that reduce water wasting, such as adopting optimal water irrigation (Cheviron et al., 2020), or the adoption

of water-saving techniques like drip-irrigation. The adoption of crops or varieties with reduced water needs is another possible objective of PEvSA programmes.

- *Environmental services for restoring connections between aquifers and dependant ecosystems*. This includes actions such as floodplain restoration and/or the re-naturation of rivers that may facilitate stream-to-groundwater exchange (Kasahara et al., 2009). In some cases, this may be compatible with maintaining agricultural activity, and be implemented through PEvSA. Though theoretically possible, we did not find concrete examples of its implementation.

The distinction between confined and unconfined aquifers and their relationship to environmental services must be mentioned here. Confined aquifers are overlain and underlain by an (almost) impervious formation, and water is stored under pressure. If the aquifer is confined, it will (almost) be not susceptible to land-use change and related pollution pressure, though it may be susceptible to pollution upstream in its recharge area. Unconfined aquifers are more susceptible to surface pollution, with variable transfer times (cf. 2.3). The reasoning behind the need for environmental services of sustainable groundwater management is the same for both aquifer types, to ensure that water uptake does not cause aquifer depletion.

A more detailed description of these environmental services is provided in Appendix 1.

EcSA users and providers

Considering the pervasive nature of EcSA, EcSA *users* are extremely diverse. For *direct ecosystem services related to aquifers*, the main beneficiaries are water consumers who benefit from the water production. This includes all direct water users: private households for domestic use, bottling companies selling mineral water, industry and farmers practicing irrigation. Domestic water users are generally too atomized to be able to enter in transactions with EvSA providers.

Users of indirect ecosystem services dependent upon aquifers are even more diverse. They may include practitioners of recreational activities associated to ecosystems depending upon aquifers, such as fishing and tourism. For example, the Poitou Marshes in western France, a large wetland directly connected to aquifers, receive more than 1.2 million tourists every year. This aquifer is largely depleted by pumping for irrigation and could create conditions of transfer between the touristic sector and farmers (Douez et al., 2020). More generally, the contribution of aquifers to maintaining ecosystem services of rivers—temperature regulation, flow throughout the season—has a positive impact on all recreational activities associated to rivers.

EvSA Providers are land users who have relevant property rights for providing environmental services related to aquifers. The main EvSA providers are farmers whose agricultural practices and choice of land use strongly influence the quality and quantity of water flowing into and out of aquifers. Other EvSA providers may be landowners or foresters, who may be either individuals or more or less organized for some aspects of the transaction.

Existing PEvSA programmes

PEvSA programmes have existed for many years, although they have not been analysed through these lenses before. The two major government-led PES programmes in Europe and in the USA, the Agri-Environmental Measures (AEMs) of the Common Agricultural Policy and the Environmental Quality Initiative Programme (EQIP), are funding many actions for improving EcSA. In 2012, EQIP allocated more than \$88 million for water quality-related conservation systems in high-priority watersheds throughout the USA. Between 2014 and 2020, EU member states have allocated €70.8 billion at EU level, for the protection of upstream ecosystems and improving water quality (no distinction is available between surface and groundwater), of which Agri-Environment and Climate Measures (AECM)—the PES programme per se—is the first instrument in budgetary terms (EEIG Alliance Environment, 2019). These programmes mainly aim at fostering the adoption by farmers of agricultural practices that reduce the impact on water quality.

Since the introduction of PES by the United Nations Framework Convention on Climate Change, under the Reducing Emissions from Deforestation and forest Degradation, or REDD+, program, PES programmes have been largely developed, especially in Latin America. Several PES especially targeted water ecosystem services, the so-called payment for water ecosystem services (PWS). In 2013, Martin-Ortega et al. already mentioned 40 PWS programmes in nine countries, to which can be added the payment for hydrological environmental services (PSAH) in Mexico (Muñoz-Piña et al., 2008), although only the latter specifically mentions the targeting of EcSA. The vast majority of these programmes pay landowners for reducing deforestation in order to, *inter alia*, maintain water-related ecosystem services.

Other PEvSA programmes have secured the quality or quantity of groundwater, through institutions in charge of drinking water production. Such programmes were implemented either by private bottling companies (Nestlé, Danone) (Chervier et al., 2017; Depres et al., 2008) or by municipalities, such as the city of Munich or New York City (Grolleau & McCann, 2012), providing incentives for farmers to reduce agricultural practices harmful for groundwater quality.

A unique example is the case of the city of Kumamoto, Japan, that has set up a PEvSA programme for redeveloping agricultural practices that increase water recharge into the aquifer, so as to secure its city water supply (Shivakoti et al., 2018; Taniguchi et al., 2019). More details about these programmes and their effectiveness are provided in 'Review of PEvSA programmes' section, hereafter, especially in the light of the challenges identified in 'Challenges of payments for environmental services related to aquifers (PEvSA) and how they could be addressed' section.

Challenges of payments for environmental services related to aquifers (PEvSA) and how they could be addressed

General issues of PES

Issues that influence the effectiveness and efficiency of PEvS programmes, whatever their target, have been largely studied in the literature. A first group of issues concerns the need for contracts to ensure a sufficient level of participants for attaining the expected results. Factors affecting participation in PES and AES can be classified into four categories: (1) farmer and farm socio-economic characteristics; (2) contract characteristics; (3) economic factors (payment level, transaction and implementation costs); and (4) behavioural factors (Calvet et al., 2019).

The second group of issues stems from the requirement of PEvS programmes to have an effective impact. This requires that:

(i) EvS providers must comply with contract requirements (*compliance issue*, Ferraro, 2008)
(ii) Contracts must result in a change of LUD that would not have occurred without the programme (***additionality issue***, Chabé-Ferret and Subervie, 2013; Wunder et al., 2008)
(iii) Land-use changes must actually lead to a desired environmental outcome, requiring the link between land use and ecosystem services to be clearly established (Engel et al., 2008) (*land use **requirement issue***)
(iv) Changes must be sustained over time (***permanence issue,*** Kuhfuss et al., 2016)
(v) Ferraro (2008) finally insists on the importance of considering the heterogeneity of opportunity cost in the design of PES, in order to avoid ES providers being over-compensated, leading to efficiency loss (*the **efficiency issue***).

Various recommendations have been proposed for addressing these widely acknowledged issues of PEvS. Several frontline authors of PES literature highlight three main recommendations for addressing such issues (Wunder et al., 2018): (i) implementation of a system for monitoring and sanctions of non-complying participants; (ii) spatial targeting of high-ES density and high-threat areas for PES enrolment; and (iii) differentiation of payment according to individual opportunity costs. In addition to these recommendations, innovative PES designs have been proposed, such as result-oriented schemes (Burton & Schwarz, 2013; Matzdorf & Lorenz, 2010), agri-environmental auction (Ferraro, 2008; Latacz-Lohmann & Van der Hamsvoort, 1997; Whitten et al., 2013), collective payment (Kaczan et al., 2017; Kuhfuss, Préget, Thoyer, & Hanley, 2016) or an agglomeration bonus (Parkhurst & Shogren, 2007).

Our aim is to identify how these common PEvS challenges apply to PEvSA. We will especially highlight whether the common PEvS issues (*compliance*, *additionality*, *land-use requirement* and *efficiency*) apply in a different way to PEvSA, due to the specifics of aquifers and ecosystem services related to aquifers. We also identify additional challenges specific to PEvSA. In each section, we explore how existing recommendations for increasing the effectiveness of PEvS could be mobilized for a better protection of aquifers. We particularly identify seven challenges:

1. The complex link between the nature of land-use change and the production of ecosystem services related to aquifers
2. Spatial features of the link between land-use change and EcSA
3. Temporal features of the link between land-use change and EcSA
4. The 'ambient' nature of EvSA and its impact on the assessment of compliance
5. The impact of the invisibility of aquifers on demand for EcSA
6. Upstream suppliers and downstream users: what implications for PEvSA financing?
7. The dilemma between efficiency and social equity in the targeting of PEvSA

The complex link between the nature of land-use change and the production of ecosystem services related to aquifers

For PEvS to be effective, land-use decisions that generate the desired EcS must indeed be stimulated (*the land use requirement issue*), but the link between LUD and EcS in general (Wunder et al., 2008), and EcSA in particular, is often uncertain. For example, many implemented PEvSA are based on the assumption of a positive relationship between forest cover and EcSA, which is not always supported by hydrological evidence (Muradian et al., 2010; Nordblom et al., 2011). In environments where water is scarce, trees and riparian vegetation that successfully tap into water resources, have shown to reduce available water volume. An analysis of surface flow in hundreds of paired-catchment experiments has indeed shown that, on average, stream flow reduces when grassland is converted to forest (Brauman et al., 2007). This has not prevented many PEvSA programmes for watershed services of fostering the development of forest cover, such as the large PSAH developed in Mexico (Muñoz-Piña et al., 2008). In fact, maintaining or developing forest cover is one of the most efficient actions for preserving water quality.

Norgaard (2010) considered that current ecological knowledge is still insufficient for accurately defining the environmental services that should underpin most PES schemes. He argued that benefits are generally assumed as a social construct, rather than through periodic monitoring of the interactions between land management and the provision of services. This often implies that, in PES schemes, important contract terms are negotiated on faith (Muradian et al., 2010). As a result, practitioners normally face a trade-off between the need to estimate efficiency gains resulting from the intervention and the need to keep transaction costs low enough for making PES schemes feasible.

For the design of PEvSA schemes, models exist that can predict the effect of a specific land-use change or management decision on the provision of EcSA (Keeler et al., 2012). For example, Herivaux et al. (2014) presented an approach that links land-use decisions with water quality. This estimates the link between LUD and groundwater-quality improvement through the modelling of nitrate fluxes, combining a hydrodynamic model and a deterministic NO_3 transfer model in the aquifers as a function of land use. It can predict the impact of LUD on NO_3 levels in aquifers over a large time horizon and can therefore facilitate the identification of targets for PEvSA implementation. A systematic use of this type of detailed modelling would, however, be too costly as a standard procedure and may actually tilt the benefit–cost ratio in favour of alternative environmental policy instruments to PEvSA (Hérivaux et al., 2014).

It is thus necessary to develop approaches with a reasonable cost, to determine which LUD should be promoted in a PEvSA programme, preferably developing several reference studies for each country that cover the different types of hydrogeological setting for guiding the construction of future PEvSA. The development of decision-making systems on the web, such as the Pesticide Fate tool (Bancheri et al., 2022), helps planners with modelling the impact of land-use change scenarios on groundwater. This is an interesting avenue for reducing implementation costs.

Spatial features of the link between land-use change and EcSA

EcSA require the combination of LUDs in the entire aquifer recharge area. Depending upon the hydrogeological context, the size of this recharge area may vary from a few hectares to thousands of square kilometres. The decisions of all land users in the recharge area therefore collectively influence the level of EcSA produced at the aquifer level. This coordination problem may cause a classical under-provision of this public good. The efforts of some, who adapt their land use, may be jeopardized by the lack of effort of others: the 'free-rider' problem.

This problem requires a PEvSA design at the aquifer scale. The first requirement is that the perimeter of the recharge area is determined. Elinor Ostrom (1990) mentioned that the first success factor of collective action is that the boundaries of the resource system are well defined. Depending upon the context, advanced hydrogeological studies must determine the concerned watershed. Contrary to surface watersheds, this does not only require a topological analysis, but also a fine understanding of the hydrogeological processes, whose complexity varies depending on the context.

Second, the integrative nature of aquifers, the fact that the actions of all land users affect downstream EcSA, requires the coordination of land users to obtain results. For aquifers with a large recharge area, this coordination can require major transaction costs. This may be particularly needed in the presence of discontinuities or thresholds, where the production of some EcSA may have a nonlinear relationship with the amount of EvSA provided by land users. For example, denitrification of groundwater naturally occurs in confined aquifers (Mariotti et al., 1988). An increase in water abstraction for agriculture may have a limited effect on this EcSA until over-abstraction causes the aquifer to become unconfined, resulting in a rapid degradation of water quality. Similar phenomena can occur in karstic aquifers of coastal areas, where certain aquifer levels may generate a sudden flux inversion from aquifer-to-sea, to sea-to-aquifer (Hakoun et al., 2021).

Other discontinuities may be generated by non-physical processes, such as regulations specifying maximum levels of contaminants in drinking water, or the threshold amounts of nitrate defined in the European Nitrate directive[3]. In such cases, EcSA can be considered as a threshold public good, with no production of the public good if the threshold of participation in the PEvSA programme is not reached (Le Coent et al., 2014). However, the commonly used PES contracts that rely on individual voluntary participation, do not include mechanisms for ensuring a minimum participation at a landscape scale (Kuhfuss et al., 2015). Several approaches have been proposed for addressing this collective-action problem. The use of collective PES has been proposed mainly in low-income tropical areas, with a promise, *inter alia*, to improve the ecological effectiveness by increasing coordination at the landscape scale (Kaczan et al., 2017), which is particularly appealing in the case of aquifers. Collective PES, nevertheless, create an additional social dilemma to that affecting users of a collective resource which is the one to freeride on others in order to receive benefits without adopting additional efforts. In their review of collective PES, Kaczan et al. (2017) mention no particular effectiveness advantage over individual PESs. Conclusions of studies focusing on LUDs carried out on privately owned land, are negative on the effectiveness of this approach (Gatiso et al., 2018; Narloch et al., 2012). Collective PES may nevertheless be the requisite instrument in the case of communal land tenure arrangements, and may be efficient for reducing transaction costs when many small farmers are targeted (Kaczan et al., 2017). Another approach for dealing with this issue is to include a collective conditionality in individual contracts, i.e. the contracts release incentive payments only if certain conditions are met. Beneficiaries, however, remain individuals even though amounts can vary depending on group performance (Kuhfuss et al., 2015). These types of PES, requiring a minimum of contracted acreage for launching the programme, have been proposed in Britanny, France (Dupraz et al., 2007) and tested in the lab (Le Coent et al., 2014). This take-it or leave-it approach may nevertheless not be in favour of a progressive adoption of the targeted land use. Other systems in which only a portion of the incentive—a collective bonus—is conditioned on a certain level of participation were pilot tested in a farm experiment with very promising results (Kuhfuss, Préget, Thoyer, & Hanley, 2016).

The impact of LUDs on aquifers can also present spatial heterogeneities, with farmers having a more or less direct influence on the aquifer depending on their location in the hydrogeological basin. For example, in karst areas, fields located near sinkholes may have a direct and rapid influence on the aquifer while areas with a less permeable underground will have a less direct effect on aquifer water quality (Kaçaroğlu, 1999). Several vulnerability mapping methods were developed for estimating this variability of contribution to the aquifer in a karst context (Marín et al., 2012). This situation can also appear in other hydrogeological settings, such alluvial plains (Hérivaux et al., 2014).

In order to improve the effectiveness of PEvSA, farmers located in the most vulnerable areas should be the primary target of enrolment. However, due to the

[3] In Europe, threshold values were defined for reaching a good chemical status of groundwater bodies (50 mg/L for $N0_3$ and 0.1 µg/L for pesticides. Directive 2006/118/EC of the European Parliament and of the Council of 12 December 2006 on the protection of groundwater against pollution and deterioration

voluntary nature of PES, it may be difficult to ensure that land users with the largest impact will indeed enrol in a PEvSA programme and adopt pro-environmental LUDs, especially when a common approach of uniform payment of land users is privileged. Some theoretical and practical innovative designs have been proposed to deal with this issue. A first approach is to restrict PEvSA to areas related to strategic aquifers. The agri-environmental measures of the Common Agricultural Policy, which can be considered a type of PEvSA (see 'Introduction' section), have included spatial targeting since the 2007–2013 CAP reform in order to improve their cost-effectiveness (Kuhfuss et al., 2013). A second approach is to ensure that land users with a strong influence on EcSA will be more likely to participate in the programme through offering them higher payments (Wunder et al., 2018). Differentiated payments can be coupled with reverse-auction systems, as in the USA with the USDA's Conservation Reserve programme (Kirwan et al., 2005), or in Australia (Whitten et al., 2013). In these approaches, a tender is launched in which land users can offer to adopt or maintain pro-environmental land use for a specific payment. Offers are selected based on this price and an indicator that evaluates the environmental effect of the proposed offer (Kuhfuss et al., 2012), that can depend *inter alia* on the location of the land. The implementation of such systems, providing it gives an advantage to land with the largest effect on EcSA, may help ensuring that land users who have the most impact on EcSA do participate in voluntary PEvSA programmes. Other designs that include an agglomeration bonus for facilitating spatial patterns of adoption have been tested in different experimental settings (Bamière et al., 2013; Parkhurst et al., 2002; Wätzold & Drechsler, 2013), but do not seem adequate for aquifers for which reaching a specific spatial pattern is not particularly relevant.

Despite their cost-effectiveness advantage, these different spatial targeting options can generate additional transaction costs. Effective spatial targeting requires that monitoring data, models or other measurement tools identify priority areas of PEvSA implementation. However, a UK study showed that the efficiency gains of differentiated payments are high enough for accommodating an up to 70% increase in transaction costs (Armsworth et al., 2012).

The spatially differentiated payment systems may nevertheless generate equity concerns. In the USA, some PES programs included spatial targeting, such as the Rural Clean Waters Program (1980s) and the President's Water Quality Initiative (1990s), but untargeted farmers claimed they were at a disadvantage for obtaining program benefits. In response, geographic targeting was forbidden by congress within the Environmental Quality Initiative Program (Ribaudo & Shortle, 2019).

Temporal features of the link between land-use change and EcSA

The time required for the production of EcS after LU changes is generally not mentioned in the PES literature. Nevertheless, this dimension can become critical for hydrogeological processes. The time transfers required for LUDs to have an impact on EcSA dramatically vary with hydrogeological settings. Water transfer from surface to aquifers can indeed vary from several hours in karst systems to thousands of years in sedimentary basins. Karst systems are thus very vulnerable to pollution, but quality can be restored very quickly. On the contrary, in a sedimentary basin, the transfer from surface to aquifer is much less vulnerable to human intervention (Hérivaux & Maréchal, 2019). In other, intermediate, contexts, water quality has been affected after years of intensification of agriculture since the 1950s, and restoring the water quality of these aquifers may take decades. For example, the use of Atrazine has been banned in Europe since 2003, but it remains one of the most common pesticides in groundwater (Chen et al., 2019). Herivaux et al. (2013) in a case study estimated that restoring nitrogen levels as requested by the European Water Framework Directive would take from 17 to 40 years, depending upon the agricultural practice-change scenario. In a recent study at the Rhone Mediterranean basin scale in France, over 41% of abstraction points were located in a context with average water renewal of more than 25 years[4]. From an economic standpoint, the existence of time dependency in the use of pooled resources, such as water, i.e. the fact that today's decisions can have long-term effects, generates inefficiencies—both in standard economic theory and in practice—due to temporally myopic behaviour (Herr et al., 1997), i.e. people do not consider the effect of their decisions over long periods.

This temporal dimension raises questions about a major feature of PEvSA contracts: the duration during which land users commit to apply the contract requirements, particularly in settings with long transfer times. In Europe, the contracts used in the Agri-Environmental Measures (AEMs) of the CAP usually last not more than 5 years. This limited duration may jeopardize the effects of PEvSA on groundwater protection, since land users may revert to previous land use at the end of their contract (Kuhfuss et al., 2016). In contexts with longer transfer times, the use of long-term contracts should thus be pursued.

A related issue is the fact that land-use change generated by PEvSA entails costs today, whereas the public benefits of agriculture change occur only in the future. As PES are considered a transaction between ES providers and ES users (Wunder, 2015), this time dependency may lead to under-production of EcSA, since future discounted benefits perceived by ES users may not overcome immediate non-discounted costs supported by ES providers. This may jeopardize attaining the first precondition for PES success spelled out by Wunder et al. (2018), i.e. that ES users' willingness to pay exceeds ES providers' willingness to accept compensation. The development of communication campaigns aiming at raising awareness of the time lag between groundwater protection policies and their effect should thus be a preliminary step for PEvSA implementation.

The 'ambient' nature of EvSA and its impact on the assessment of compliance

One of the important conditions for PEvS effectiveness is to ensure that EvS providers do implement the required land-use change (*the compliance issue*). Monitoring individual decisions of land users and applying a penalty system can represent

[4] https://www.eaurmc.fr/jcms/pro_101439/fr/guide-technique-sdage-captages-eau-potable-prioritaires-aout-2020

significant transaction costs due to the scattered nature of land users and the difficulty to police some land-use decisions (Choe & Fraser, 1999). This may be particularly costly in the case of PEvSAs where some LUDs may be difficult to observe, such as fertilizer or pesticide use. The implementation of result-oriented rather than traditional action-oriented contracts may be a solution for solving this problem (Burton & Schwarz, 2013; Matzdorf & Lorenz, 2010). However, this requires that the individual actions of land users on EcSA can be inferred from the observation of groundwater state or associated services, which is generally impossible. For example, Despres et al. (2008) argue that it is prohibitively costly to impute the individual responsibility of nitrate-rate decrease in an aquifer, jeopardizing the possibility of paying farmers according to the nitrate rate in the aquifer. Action-oriented PEvSA contracts thus remain largely dominant, as observed in the Latin–American PES for water services (Martin-Ortega et al. 2013).

Segerson (1988) proposed a contract adapted to the case of non-point-source pollution, where many polluters may jointly contribute to pollutant levels in aquifers, while their individual actions or discharge levels are impossible, or very costly, to observe or infer. She proposed an individual incentive mechanism known as the 'ambient tax', directly dependent upon overall pollutant levels in the aquifers. Its amount is set at the total estimated damage by the ambient pollution. Although optimal in theory, this type of mechanism has not been feasible for implementation, considering the absence of political acceptability of adopting prohibitive tax amounts (although they are theoretically not paid due to their effectiveness). The use of ambient groundwater-level indicators has also proved not to be efficient in the past for limiting groundwater overdraft. This type of approach has indeed led farmers—at the approach of warning levels—to increase irrigation for building up soil moisture (J. D. Rinaudo, 2020). It has also led to investing in the increase of irrigation capacity, in order to cover irrigation needs over a shorter time, resulting in the development of volumetric management and the definition of individual water abstraction limits.

Although result-oriented payment schemes based on ambient indicators of aquifer condition may not be feasible, the use of indicators that are proxies for the actual implementation of individual LUDs can be a valid alternative. For example, the nitrate balance before winter is a good indicator of the risk of nitrate leaching in aquifers during winter, and may be better adapted than indicators based on nitrate use. This indicator is currently experimented in the CPES Interreg project at Tremblay-Omonville, France[5]. The generalization of water-meters in irrigation (Chabé-Ferret et al., 2019), for measuring water uptake at the individual level, may also provide valuable data for building PEvSA for the sustainable management of water resources.

The impact of the invisibility of aquifers on demand for EcSA

EcSA demand is marked by the limited knowledge of users on aquifers, hydrogeological processes and their related services. Groundwater receives less

[5] https://www.cpes-interreg.eu/fr/projet-cpes/nos-sites-pilotes/bassin-d-alimentation-de-captage-de-tremblay-omonville

attention than surface water, because it is much less visible and pollution problems are not as obvious as those of surface water, e.g. dead fish or algal blooms (Kløve et al., 2011). Herivaux and Rinaudo (2016) estimate in a survey carried out on two sites (Liège, Belgium, and Lorraine region, France) that understanding of aquifers and related issues is very limited; 76% of the respondents in the Liège case know nothing of aquifer/groundwater contamination and 54% of the respondents in the Lorraine region know nothing about groundwater over-pumping. Similar trends are observed in Latvia (Pakalniete et al., 2006), the Netherlands (Brouwer et al., 2006), Eastern France (J. Rinaudo & Aulong, 2014) and in Massachusetts, USA (Stevens et al., 1994). This awareness is likely to be even more limited for the EcS bundle that depends upon aquifers, such as the indirect impact of aquifers on ecosystems (Hérivaux & Rinaudo, 2016). The role of groundwater in wetlands and streams is indeed often complex and poorly documented (Kløve et al., 2011).

This limited knowledge is likely negatively to influence demand for EcSA by users, resulting in limited opportunities for developing direct PEvSA programmes, and in limited pressure on decision makers to develop government-led PEvSA programmes. The implementation of communication campaigns to raise EcSA awareness thus is a key step for ensuring support for PEvSA and other public policies related to aquifer protection. This should go beyond the use of scientific representations, and make more use of mass-media techniques, such as artistic representations, to reach a broader audience by showing the social and political dimensions of groundwater (Richard-Ferroudji & Lassaube, 2020). The use of labelling that certifies EvSA production by farmers may further promote public support for PEvSA, as was done in the managed aquifer recharge of Kumamoto, Japan (see 4.6).

Upstream suppliers and downstream users: what implications for PEvSA financing?

Improving EcSA production, such as producing good-quality water or conserving aquifer-dependant ecosystems, requires modification of LUDs. This should be done in the recharge area of the aquifer, where PEvSA are generally implemented. The costs associated with LUD are thus borne by upstream land users, but the benefits associated with EcSA are generated downstream. This classic upstream-downstream solidarity issue creates specific challenges for PEvSA.

Ensuring the link between downstream demand for EcSA and upstream implementation of EvSA requires the existence of governance mechanisms at the aquifer level. The use of intermediary institutions between EcSA users and EvSA providers is a key step in many situations. In over 81% of Latin American water PES schemes (Martin-Ortega et al., 2013), an intermediary exists for accommodating the transactions, while the remainder are direct transactions between buyers and sellers. This system also requires the implementation of a financing mechanism to ensure the transfer from service users to service providers.

Efficiency or social equity in PEvSA

There is a debate between scholars on whether PES should focus on efficiency, or on social equity criteria (Karsenty et al., 2017). This debate boils down to either targeting farmers on efficiency grounds, generating the largest environmental changes at the least cost as they generally are the largest polluters (the marginal cost of pollution abatement is generally increasing; Tietenberg & Lewis, 2016), or to reward land-users that already adopt pro-environmental practices, on equity grounds.

This debate is particularly vivid in the context of PEvSA, since the most intensive farmers, who irrigate their crops or use the most chemical fertilizers and pesticides, are the ones who have the largest negative impact on EcSA. Other types of land use, such as extensive farming with crop rotation and low input use, may actually have a positive impact on aquifers. An economic efficiency analysis clearly recommends targeting land users with the lowest marginal pollution abatement costs, generally the largest polluters. For example in the Mississippi River Basin, 10% of cropland is estimated to contribute 30% of the nitrogen load from cultivated cropland to the Gulf of Mexico (White et al., 2014). Targeting these intensive farmers would thus enhance program cost-effectiveness (Ribaudo & Shortle, 2019). There are, however, economic arguments that may justify the targeting of virtuous land-users. First, less intensive farming that generates a positive impact on EcSA may actually be threatened due to limited economic profitability. Providing incentives for these farmers may facilitate the maintenance of their system over time, and avoid their replacement by more intensive farms that would cause further EcSA degradation. On the contrary, providing incentives to intensive farms may strengthen the profitability of these farm models over time, although they still generate negative externalities (Ribaudo & Shortle, 2019). Finally, from a wider policy perspective, favouring the reward of virtuous land users may signal nature conservation as a valuable social objective, and encourage present and future environmentally friendly behaviour (Muradian et al., 2013).

This question also refers to the determination of a reference level, above which a change of LUD may be considered as an environmental service and be rewarded, and below which LUD should be considered as generating negative externalities and be subject to the 'polluter pays' principle (Lindhout & Den Broek, 2014). The determination of this reference point when implementing PEvSA may differ from EcSA related to water quality and water quantity. Regarding the environmental services of sustainable groundwater management, the Water Framework Directive in Europe obliged member states to take action for ensuring that water resources and associated ecosystems were restored to satisfactory quantitative and qualitative levels. In France, this translated into an obligation to restore a balance between abstraction and available resources for all catchment areas (J. D. Rinaudo, 2020). This has led, in areas marked by groundwater depletion, to the definition of maximum volumes to be abstracted, or individual water quotas, distributed among land users by different methods. In case PEvSA would need to be developed in these contexts, the water quota level should be considered a reference point for PEvSA.

For environmental services for protecting upstream ecosystems, the reference point has been defined for Agri-Environmental Measures of the CAP, targeting the

Table 1 PEvSA issues and available PES features and designs for overcoming them

PEvSA issues	Possible solutions
Link between land use change and EcSA	Modelling reference cases at national level in diverse hydro-geological settings to determine guidelines for selecting land-use requirements in contracts (Hérivaux et al., 2014)
Spatial dimension	– Spatial targeting (Armsworth et al., 2012). – Differentiated Payments(Wunder et al., 2018) and Auction systems (Kirwan et al., 2005, Whitten et al., 2013) – Collective bonus (Kuhfuss et al., 2016) – Use other policy instruments in very sensitive areas
Temporal dimension	– Adapt contract duration to the time required for obtaining effective results – Compromise between increasing contract duration and reaching more farmers (Bougherara and Ducos, 2006; Ruto and Garrod, 2009; Vaissière et al., 2018) – Use other policy instruments when time transfers are too long (AERMC, 2020)
Ambient nature of aquifers	– Impossibility to implement result-oriented schemes based on groundwater indicators (Despres et al., 2008) – Use result-oriented rather than action-oriented contract based on intermediate results
Invisibility of aquifers	– Communication campaigns for stimulating EcSA demand (Richard-Ferroudji & Lassaube, 2020). – Labelling of products enrolled in PEvSA programme (Grolleau and McCann, 2012, Shivatoki et al., 2018)
Upstream supplier-downstream users	– Financing mechanisms and intermediate institutions for channelling downstream demand to upstream EvSA providers.(Martin-Ortega et al., 2013)
Efficiency vs Social equity	– Trade-off between 'virtuous circle' and efficiency approach (Ribaudo & Shortle, 2019, Muradian et al., 2013) – Minimum reference level for eligibility to payments must be defined (Lindhout & Den Broek, 2014).

improvement of surface and groundwater water quality. All farmers entering in these contracts should first respect statutory management requirements that include rules on public, animal and plant health, animal welfare, and the environment. This entails the respect of the Nitrate Directive that includes precise rules in vulnerable areas: maximum amounts of nitrate to be used, timing of fertilization, maximum carrying capacity of animals and the obligation to use cash crops. In addition, farmers receiving CAP support must respect EU standards on good agricultural and environmental condition of land (GAEC), such as a ban on cutting hedges during bird breeding/rearing season, the maintenance of permanent grassland, the respect of irrigation authorizations and the protection of groundwater against pollution[6]. In Europe, only LUDs that go beyond this minimum reference point can benefit from future PEvSA programmes.

[6] https://ec.europa.eu/info/food-farming-fisheries/key-policies/common-agricultural-policy/income-support/cross-compliance_en

We argue that setting these reference levels is a key feature for the implementation of any PEvSA.

Table 1 summarizes the PEvSA issues and available PES features and designs to overcome them.

Review of PEvSA programmes

We carried out a literature review to identify existing PEvSA programmes. Relevant literature was identified via computerized searches on the Web of Science and Google Scholar, using the terms: 'payment for ecosystem services', 'payment for environmental services', 'agri-environmental schemes', combined with 'water', 'groundwater' and 'aquifers'. Based on this research, we identified six main types of PEvSA programmes: the AEMs of the European CAP, the Environmental Quality Incentives Program (EQIP) in USA, the Latin American PEvSAs, city PES programmes to secure public drinking water supply, and the mineral water PEvSA and PEvSA for Managed Aquifer Recharge. We then illustrate how these programmes handled challenges highlighted in 'Challenges of payments for environmental services related to aquifers (PEvSA) and how they could be addressed' section (summarized in Table 2) and provide evidence of their effectiveness.

The European AEMs

Agri-environmental measures (AEMs) of the CAP (called agri-environmental climatic measures in the last CAP) represent one of the largest PEvSA programmes implemented in the world. AEM contracts, generally referred to in the scientific literature as agri-environmental schemes (AES), were introduced in Europe in the early 2000s. During the 2014–2020 CAP, AEMs were used for supporting (EEIG Alliance Environment, 2019; Menet et al., 2017):

- The creation and maintenance of sustainably managed grassland or wetland
- The maintenance of soil cover for water purposes (e.g. protection of water against erosion and pollution through introduction of winter crops in eroded areas)
- The implementation of specific crop-management practices, such as stubble ploughing for increased water retention in soil
- The limitation of phytosanitary and fertilizer products used
- The adoption of less water-intensive crops or varieties
- The adoption of improved water-management strategies

The amount of land covered by these measures varies between countries, with about 9% of agricultural land covered by these measures at the EU level (EEIG Alliance Environment, 2019). It was primarily aimed at restoring water quality in

Table 2 Summary table of how existing PEvSA programmes have addressed challenges highlighted in the previous section

	European AEMs	EQIP programme	PEvSA in Latin America	City PES for drinking water (Munich, Germany)	Mineral water PEvSA programmes (Vittel, France)	PEVSA for Managed Aquifer recharge (Kumamoto, Japan)
Link between land use change and EcSA	Local choice of LU change among pre-established lists.	Qualitative evaluation of impact of conservation practices and watershed studies (CEAP) but with limited groundwater results	Priority on avoiding deforestation with limited evidence of the impact on EcSA	Priority on organic agriculture	Hydrogeological modelling to design prescribed land use change	Hydrological modelling to identify practices
Spatial dimension	Spatial targeting at water catchment level	Priority watersheds identified in terms of nitrogen leaching, irrigation acreage and groundwater depletion areas	Targeting based on estimation of deforestation risks (PSAH-Mexico)	Catchment area for drinking water abstraction and priority to vulnerable areas	Target area identified through modelling	Hydrological modelling to identify key recharge areas
Temporal dimension	Not considered. 5-years standard contracts	Not considered. 5-years standard contracts	Not considered. 5-years standard contracts mainly	Long term contracts: 6-12 years	Very long term contracts: 30 years	No information but less relevant because rapid transfers
Ambient nature of aquifers	Action oriented contracts	Scoring rules to estimate the impact of proposed agricultural practices	Tiered payment with higher payment for LUD with higher results (cloud forest conservation in PSAH -Mexico)	80% of the targeted area under contract.	96% of targeted land under contract	Payments for flooding of rice fields with direct effects on recharge
Invisibility of aquifers	Not considered	Not considered	Not considered	Communication campaign on the link between organic agriculture and water quality	Not necessary (one main EcSA user)	Communication campaign and development of an eco-label

Table 2 (continued)

	European AEMs	EQIP programme	PEvSA in Latin America	City PES for drinking water (Munich, Germany)	Mineral water PEvSA programmes (Vittel, France)	PEVSA for Managed Aquifer recharge (Kumamoto, Japan)
Upstream supplier-downstream users	Government/ European funded programmes	Government funding	Intermediate institutions key to success (81.6% of PWS)	Municipality programme	Creation of an advisory firm	Oversight from a local agricultural organization and funding mechanism from major ground water users.
Efficiency vs Social equity	Legal minimum set of practices for eligibility to CAP. Co-existence of measures targeting the largest polluters and measures to maintain good agricultural practices from virtuous farmers	Other priorities involved in contract allocation than cost-effectiveness such as target social groups	Poverty reduction is an important secondary objective in Latin-America with possible competition with efficiency	*No information*	*No information*	*No information*

surface- and groundwaters (*Environmental services for protecting upstream ecosystems*). The quantitative aspects of water conservation (*Environmental service of sustainable water management*) are in priority handled through alternative policy instruments, such as volumetric approaches. Menet et al. (2017) nevertheless showed that measures for supporting sustainable groundwater management are rather water allocation rules, such as quotas and water tariffs, and investment subsidies for water-efficient technologies, such as drip irrigation.

Targeting in terms of the type of LUD change and the selection of priority areas is a major concern in AEM implementation. In France, AEMs for protecting upstream ecosystems can be contracted only in priority catchments that face water-quality issues (*spatial targeting*). EEIG Alliance Environment (2019) showed that such targeting led to relatively high implementation and control costs, compared to other rural development measures (over 60% are personnel costs in some Member States). AEMs, however, were found to be a significant driver for encouraging the adoption of practices beneficial to water quality and quantity, especially for promoting systemic changes; the administrative burden associated with this measure appears, overall, appropriate for ensuring adequate control (EEIG Alliance Environment, 2019).

The *temporal dimension* for obtaining an effect on groundwater has been largely eluded in the design of AEMs for water. Contract duration is generally set at 5 years, which is insufficient for generating a significant impact in many cases. EEIG Alliance Environment (2019) confirms that AEMs for limiting the use of phytosanitary products are only effective in the long term. This means that farmers should re-enrol every 5 years, creating the risk that they drop out of the scheme, increasing the administrative burden. However, as mentioned before, the limited contract duration increases the acceptability of an AEM. Contracts used in the AEMs are action-oriented and generally do not include a result-oriented component even intermediate (*ambient nature*).

Limited references exist on the effectiveness of the CAP AEMs for groundwater protection. Slabe-Erker et al. (2017) used a spatial-panel econometric analysis for assessing the impact of agricultural payments on groundwater quality in all municipalities of Slovenia. They identified a very limited effect of AEMs on pesticide-use reduction and a counterproductive positive effect on nitrate loads. Their study, however, only partially considered the temporal dimension of transfers, as they studied an only 2-year lag for the potential effects on groundwater of adopting an AEM. Other studies found evidence of intermediate outcomes, such as a modification of agricultural practice, including crop rotation and soil cover plants, but at the cost of large windfall effects (Chabé-Ferret & Subervie, 2013): a decrease of agrochemicals use and an increase of grassland area in Germany (Pufahl & Weiss, 2009) and in Wales (J. I. Jones et al., 2017), a reduction of herbicide use in viticulture in France (Kuhfuss & Subervie, 2018), and a negative relationship between agri-environmental expenditures and nitrogen surpluses at the European level (Reinhard & Linderhof, 2015). This evidence suggests that AEMs may indeed have effect on groundwater quality through the reduction of pollution pressure, although the relatively high transaction costs affect economic efficiency.

Menet (2017) studied the effectiveness of AEMS aiming at the *Environmental service of sustainable water management*, through the adoption of new crops. He found a very limited participation of farmers mainly due to (i) the high risk associated with adopting a new crop, (ii) the limited technical support provided to farmers and (iii) the lack of functional supply chains for new crops. The type of land use promoted is questionable, with, for example in the French case, the substitution of maize by soybean, which causes very limited reduction in water use. The compliance issue is generally not addressed, since the schemes focus on the modification of practice or crops, but do not include water-use criteria, except in the Cyprus and Greece cases that had water-use reduction objectives. In none of the cases were the results in terms of water-consumption reduction used for conditioning payments to farmers. The general impact in terms of water-use reduction has not been evaluated in any of the cases, casting doubts on the overall effectiveness of this approach. Spatial targeting was implemented only in the Greece, Cyprus and Romania cases, with the targeting of water-abstraction reduction from aquifers only in the Cyprus case.

The EQIP programme

The EQIP programme was created by the 1996 Farm Act and has been re-authorized in subsequent farm acts (Liu et al., 2018; Wallander & Hand, 2011). EQIP's main purpose is to enhance farmers' production incentives, improve water quality, reduce soil erosion and protect the sustainability and stability of the ecosystem with the provision of financial and technical assistance. Although administered and funded by the federal government, the EQIP programme broadly functions as a PEvS where voluntary agriculture producers will be compensated if they adopt conservation farm management practices on a cost-share basis with USDA/NRCS. The total budget of the programme had reached $1.4 billion in 2016. The list of conservation practice to be used in EQIP is standardized in the NRCS National handbook of Conservation of practices. In the 2018 Farm Bill, 10 conservation practices are eligible for increased payments per states. The two first priorities are (1) reducing excessive nutrients in ground or surface water, and (2) addressing the conservation of water to advance drought mitigation and declining aquifers, witnessing the importance of EcSA (USDA-NRCS, 2020).

In order to identify appropriate conservation practices, NRCS has established the Conservation Practice Physical Effects documents which provide qualitative information on the impact of all conservation practices on natural resources, including groundwater depletion and transport of nutrients to groundwater. In addition, the Conservation Effects Assessment Project (CEAP) has established since 2003 the Watershed Assessment Studies to provide in-depth analysis on the effect of conservation practices at the watershed scale, with fourteen benchmark watersheds. The compilation of 15 years of research presented in Moriasi et al. (2020) however reveals limited evidence on the impact of agricultural practices on groundwater (*Link between land use change and EcSA*).

High priority areas and priority resource concerns are identified in each State to target payments (S*patial dimension*). The CEAP developed a classification system of watersheds based on inherent vulnerability, or level of environmental concerns, and the conservation practices that had been implemented affecting that watershed. CEAP classified acres as high, moderate or low needs, with high needs acres showing the greatest imbalance between site vulnerability and current conservation. However, according to the US-Government Accountabilty Office (US-GAO, 2017), spatial targeting is estimated to have had a limited impact on the allocation of funding which remains primarily based on historical funding. EQIP is based on 5 years contracts with no particular provision for the *temporal dimension* required for the effectiveness of EvSA.

In order to maximize impact, NRCS evaluates and prioritizes farmers' applications using ranking tools taking into account the magnitude of anticipated environmental benefits that will result from the proposed practices in the application compared to costs; whether the practices in the application will help the applicant meet regulatory requirements, such as water quality regulations; and other locally defined pertinent factors (*Ambient nature*). However, in the report 'EQIP Could Be Improved to Optimize Benefits' (US-GAO, 2017), US-GAO indicates that NRCS effectively uses ranking tools that does not accurately value environmental benefits and gives cost-effectiveness a weight that is too low to have a meaningful impact on which applications are selected. NRCS indicates that cost-effectiveness represents only 10% of the ranking scores because they have many goals to balance when making allocation decisions, including statutory requirements to direct certain percentages of funds to specific environmental concerns and certain participant groups and to involve state and local stakeholders in priority-setting decisions (*Efficiency vs social equity*).

There is limited evidence on the impact of the EQIP programme on water EcS and even less on EcSA. Wallander and Hand (2011) estimated the impact of EQIP support for the investment in water-saving irrigation practices on water application rates and irrigated acreage. Program rules require that EQIP participants who receive payments for water-conservation purposes actually reduce water use on the farm, rather than simply increasing efficiency and using the water savings elsewhere. The analysis shows that when correcting for selection bias, considering that participation is voluntary and that participating farmers may be different from non-participants even before participation, there is no evidence that EQIP may have had a measurable effect on water conservation. Similar findings are discussed by Pfeifer and Lin (2010), who—using a structural econometric model of crop choice and groundwater extraction—provided theoretical and empirical evidence that the incentive programs for water-saving technologies, in fact resulted in yield increase, shifting to more water-intensive crops, and expanding irrigated acreage. This 'Jevon paradox' is observed in other, similar, incentive programmes in the world (Sears et al., 2018).

Liu et al. (2018) investigated the impact of water-quality conservation programmes. The main practices encouraged included Prescribed Grazing (30%), Integrated Pest Management, Nutrient Management, No-Till or Strip-Till Residue Management and Conservation Crop Rotation. They aggregated multiple datasets at national level on a yearly basis and at watershed scale. This included monitoring water quality in streams (8 million observations), EQIP payments, watershed information, agriculture and economic statistics. They found that EQIP payments significantly reduced nitrogen loads in streams. Using a GIS modelling approach, Thomas et al. (2007) estimated on the contrary that the nutrient management plans funded under the EQIP programme had a very limited impact on the reduction of nitrate load in surface waters and shallow aquifers in Indiana. They attributed this to the lack of targeting farmers that use the most nitrate as well as the scattered adoption of EQIP due to a lack of spatial targeting in priority watersheds.

PEvSA in Latin America

Latin America has pioneered the implementation of PEvS programmes since the early 2000s. Martin-Ortega et al. (2013) present a review of 40 different payment for water ecosystem services (PWS) in nine Latin American countries. No information is available on whether these programmes targeted groundwater or surface water. We analysed this review of PWS that we completed with an analysis of the payment for hydrological environmental services (PSAH) in Mexico, which provides specific information on aquifers, especially in terms of targeting (Muñoz-Piña et al., 2008).

As most PES implemented in Latin America, the main target of PWS is forest conservation and to a lesser extent forest management, with more than 80% of transactions targeting this type of management decision (Martin-Ortega et al., 2013). Less than 20% of transactions cover agricultural and agro-forestry practices. In Mexico, avoiding deforestation is the only targeted land-use change of the PSAH. This focus is made despite uncertainty on the direct link between deforestation and its quantitative impact on surface- and groundwater, except in particularly steep aquifers for reducing erosion, or in the case of cloud forest that captures water from fog during the dry season (Muñoz-Piña et al., 2008). In practice, however, only 10 to 15% of PSAH transactions cover cloud forests where the actual *link between land-use changes and available water quantity* is confirmed. These programmes thus mainly aim at improving the overall impact on water-related ecosystem services (notably those related to water quality) and other ecosystem services associated with forest cover (biodiversity, carbon sequestration), with potentially limited or no impact on quantitative water availability, although this objective is often part of the programme justification.

In terms of *spatial targeting*, Muñoz-Piña et al. (2008) report interesting approaches of the PSAH. An econometric model was first designed for identifying characteristics leading to higher deforestation risks. These characteristics were then used for the targeting of project areas with a higher risk of deforestation. In addition, the project used an indicator of over-exploited aquifers to define eligible areas of project implementation. As a result, 10 to 25% of the project resources have gone to areas with over-pumped aquifers.

The *temporal dimension* associated with PEvSA is largely overlooked in PSAH with 5-year contracts. More diversity of contract duration is reported from Latin American PWS, but still with a median contract duration of 5 years. Interestingly, the contract duration choice of PSAH was made to allow the enrolment of sizeable amounts of forest every year, rather than securing smaller amounts of land for longer periods.

The objective of most PWS is to improve the storage and supply of good-quality water (Martin-Ortega et al., 2013). Despite this objective, most programmes use action-based contracts rather than result-oriented ones. For improving results, most programmes use tiered payments, with higher payments for actions supposed to yield better results, such as cloud-forest conservation in the PSAH. It should, however, be noted that both Martin-Ortega et al. (2013) and Muñoz-Piña et al. (2008) provide no evidence of EcSA results, but only estimates of the impact on deforestation, or the result of actions (*Ambient nature*).

Finally, these programmes confirm the importance of intermediate institutions for linking ES demand and supply (81.6% of PWS) (*Upstream supplier-downstream users*). They also raise another dimension of equity, which is the targeting of poor land users, often an additional objective of PES programmes in developing countries that may compete with efficiency objectives (*Efficiency vs Social equity*).

City PES programmes for securing drinking-water supply

Large cities increasingly wish to secure their drinking-water supply, to face present and futures issues related to urban growth, the degradation of water quality due to the intensification of agriculture, and the adaptation to climate change (Koop & van Leeuwen, 2017). This has led large cities in Europe to start developing PES programmes beyond the AEMs proposed in the Common Agricultural Policy.

The case of Munich is an emblematic example of this type of PES programme (Grolleau & McCann, 2012). It is the third largest city in Germany with about 1.2 million inhabitants. About 80% of drinking water, 90 Mm^3, is extracted from springs in the Mangal valley. In the 1980s, Munich experienced a surge of nitrate load in drinking water resources. In 1991, the city decided to develop a PEvSA programme, for farmers in the catchment areas to adopt organic farming and improve the quality of groundwater used for water supply. The *temporal dimension* related to restoration of the groundwater quality was managed by proposing long-term contracts, with an initial duration of 6 years that could be extended for an additional 12 years. The s*patial dimension* was taken care by proposing contracts in the most vulnerable areas. This initiative benefited from the positive market prospects of organic products and the fact that the city purchased large quantities of such products for supplying its schools and municipal restaurants. A special effort was also made for improving the public visibility of the link between agricultural practice and water quality with the campaign: ‘One litre of Bio milk contributes to the protection of 4000 litres of Munich’s drinking water’ (*Invisibility of aquifers*).

The results of this programme (Grolleau & McCann, 2012) are significant: 80% of the targeted area was put under contract for improved water quality (*Ambient nature*). Nitrate levels came down to 7 mg/L and some pesticides containing terbuthylazin descended to 0.02 µg/L. The price increase for water consumers due to this water-protection effort is estimated to be 0.005 €/m^3, whereas the avoided cost of water treatment equipment was estimated at 0.23 €/m^3. Similar programmes following the same type of approach have emerged in other European cities, such as Paris, Rennes and Lons le Saunier in France and Freising in Germany.

Mineral water PEvSA programmes

Among the most famous and earliest PEvSA programmes is probably the Vittel case (Depres et al., 2008). This programme was developed in response to the quality degradation of the Vittel Mineral Water exploited by Nestlé in the French Vosges Mountains, with a significant increase in nitrates. The main cause was identified as non-point source pollution from intensive farming around the Vittel springs (37 farmers, 3500 ha), creating a risk of closing this exploitation. After studying different options, including land acquisition, Nestlé Waters finally opted for a PEvSA, considered as the most cost-effective solution.

The *link between land use change and EcSA* in terms of nitrate rate reduction is complex and nonlinear in this area, so the LUD change was designed with a research institute. Modelling concluded on the need for reducing the land carrying capacity to one cow per ha, to eliminate maize crop, to ban pesticides, to reduce mineral fertilization, to modify farm buildings and to make manure composting mandatory. PEvSA contracts were proposed to all farmers in the catchment of the Vittel Spring, with narrower spatial targets for the farmers near the most sensitive area of the spring. The Vittel PEvSA particularly considered the *temporal dimension* of restoring the aquifer and thus signed long-term contracts for 18–30 years. To ensure compliance of land users with contract requirements and because of a lack of practical observability, Vittel had to set up an advisory firm that could provide technical support to farmers (*Upstream suppliers downstream users*). The Vittel PEvSA was considered a success, with 92% of farmers and 96% of the land enrolled (*Ambiant nature*). Although Vittel is an almost perfect case of PEvSA, the possibilities for upscaling this type of scheme remain limited, considering the transactions costs of setting up and operating this system, which were justified here by the large profits made by the company from the mineral water.

Similar PEvSA for protecting upstream aquifers were developed by Danone in France (Volvic, Evian, Badoit, Salvetat) and in Indonesia (Aqua) (Chervier et al., 2017). In the case of Volvic, a PEvSA helps reducing or preventing the use of chemical inputs, supports the conversion to organic farming and improves the management of manure. Similar features, such as large investments in hydrogeological knowledge and investments in technical support to farmers, are considered important success factors of the programme.

PEvSA for managed aquifer recharge

Few examples of PEvSA programmes for supporting Managed Aquifer Recharge are documented. We present two cases: the Groundwater Offsetting scheme in Kumamoto, Japan (Shivakoti et al., 2018; Taniguchi et al., 2019), and the Crau plain in southern France (personal observation).

The aquifers below the city of Kumamoto, Japan, provide drinking water for 730,000 inhabitants. Before the programme, groundwater levels had been declining since the early 2000s, mainly due to increased pumping and urbanization, and the abandonment of rice paddies in the main upland recharge areas, associated with a decline in seasonal land flooding. In 2004, the Kumamoto City government introduced a PEvSA programme to pay farmers for flooding fallow rice paddies during 30 to 90 days with river water, in order to recharge the groundwater system below the city. Over the period 2004–2017, an average of 456 farmers participated in the programme each year, irrigating 460 ha of paddies per year. A total of 48.6 million JPY (427,921 USD) was paid in subsidies per year, and an estimated 13.7 million m^3 of water was recharged each year. The programme is considered a large success, with the recovery of the groundwater table having stabilized at levels comparable to pre-industrial levels in the 1950s (Shivakoti et al., 2018).

Different PEvSA issues were addressed in this project. The technical design of the programme was based on hydrogeological modelling for identification of management practices and key recharge areas (*Link between land use change of EcSA and spatial targeting*). The oversight of a local agricultural organization that monitors and controls farm activities was instrumental in project implementation and transaction-cost reduction. In addition, a financing mechanism was set up for solving the upstream-downstream issue. After consultation with stakeholders, an offsetting scheme was devised, in which major groundwater users (Kumamoto City water utility and the private sector) agreed to finance the scheme (*Upstream supplier-downstream users*). To strengthen demand for EcSA, a communication campaign on the benefits of groundwater recharge was run and the rice produced in farms along the Shirakawa River now is eco-labelled. The programme communicates on the fact that purchasing 1 kg of eco-rice is equivalent to recharging 20 m^3 in the aquifer (*Invisibility of aquifers*).

Although the Kumamoto example is unique, a similar PEvSA programme is under development in the Crau Plain in southern France. A traditional gravity-fed irrigation of grassland for sheep farming exists since decades in the area. Water taken from the Durance River is used for irrigation as well as for recharging the Crau aquifer, which is strategic for drinking water and fruit production in the area and for avoiding salt intrusion into the aquifer. The decline of this traditional sheep production system may jeopardize this equilibrium. A PEvSA programme for maintaining this recharge is currently under development[7].

Another pilot MAR programme, the Recharge Net Metering (ReNeMet) project, is under development in the Pajaro Valley in California, USA (Miller et al., 2021), for incentivizing farmers to infiltrate stormwater into the aquifer. The originality of this system is that incentive payments are provided as a rebate of the pumping fee they have to pay for water used for irrigation.

Discussion and conclusions

This paper is a first attempt at characterizing payments for ecosystem services related to aquifers. PEvSA are defined by specific issues, due to the nature of ecosystem services related to aquifers. Some relate to the complexity of the links between land-use change and impacts on EcSA—the spatial, temporal and integrative nature of aquifer processes—others relate to the disconnection between

[7] https://www.symcrau.com/index.php?option=com_content&view=category&layout=blog&id=72&Itemid=566

EvSA offer and EcSA demand, due to the invisibility of aquifers and upstream-downstream relationships, and by the efficiency *versus* social-equity dilemma. This inventory of challenges relies both on a review of the processes of Ecosystem Services related to aquifers, as well as on a review of Payment for Environmental services. We present a subjective list of challenges deemed significant for the effectiveness of PEvS, and then review the PEvS literature to highlight features and innovative designs that may help overcome PEvSA challenges.

While PEvSA are presented as new policy instruments in some policy arenas, we identified some earlier large-scale PEvSA-like programmes in different parts of the world. We only describe programmes presenting some evidence of impact published in the scientific literature or official reports, and excluded new initiatives. Hence, despite their interest, we have excluded new interesting initiatives such as the 150 M€ PES programme launched in 2020 in France. We also present the most significant programmes and those considered illustrative of the diversity of stakeholders involved and the diversity of objectives of PEvSA. We note that they overwhelmingly aim at strengthening the environmental service of protecting upstream catchments, mainly to improve or maintain the quality of groundwater, or—to a lesser extent—to increase or maintain the quantity of water recharged into an aquifer. We found very few examples of programmes targeting sustainable groundwater management, such as some agri-environmental measures of the CAP for adopting less water-intensive crops by farmers, and no examples were found of programmes targeting the connections between aquifers and dependant ecosystems.

Our analysis of PEvSA programmes reveals how the challenges we have identified are taken into account in the main existing programmes, leading to recommendations for the future development of PEvSA.

We determine that land-use changes supported in PEvSA programmes are rarely based on modelling of the link between land use and EcSA. Land-use change is mostly based on the potential positive impact determined by expertise, or may even be based on social constructs (Norgaard, 2010), or the preference for land-use change due to other environmental benefits (Latin American PWS). Advanced hydrogeological modelling was only carried out when large monetary benefits are at stake for EcSA users, such as in the case of a mineral water PEvSA (Depres et al., 2008). We therefore confirm that science-based approaches for determining land-use prescription should be more promoted for the design of future PEvSA, in order to establish reusable reference studies for various hydrogeological settings, so as to avoid excessive transaction costs.

Spatial targeting of land-use change in an area of aquifer recharge is a widespread practice. However, more refined rules, such as differentiated payment to land users in areas with the highest potential contribution to EcSA, or the use of collective conditionality or bonuses, could not be documented. Some experiences of differentiated payments in priority areas, such as cloud forest in the Mexican PSAH (Muñoz-Piña et al., 2008), exist, but in other cases differentiated payments based on spatial contribution are rejected on equity grounds, such as in the EQIP programme (Ribaudo & Shortle, 2019). Interviews with promoters of the new PEvS programme launched in France in 2020 show that the option of a collective bonus to foster higher participation of farmers and obtain significant results was rarely included in local programmes, due to reluctance of the project promoters. Investigating the discrepancy between the positive acceptability of innovative design in the literature (Kuhfuss et al., 2014) and the reluctance of programme promoters to activate such design, despite its benefits, is an interesting avenue for future research.

Two different approaches to address the time dimension of EcSA are used in PEvSA. In some limited cases, such as the mineral-water PEvSA examples, long-term contracts are offered that comply with realistic transfer times in the system. In most other cases, due to budgetary constraints, such as in AEM, short-term contracts (5 years) are privileged so as to reach a large number of farmers. This approach relies on the (questionable) assumption that participation in one contract term will lead to sustainable practice change, which is uncertain (Kuhfuss, Préget, Thoyer, Hanley, et al., 2016). Despite their potential impact on contract acceptability, longer-term contracts more aligned with pollutant transfer times in aquifers should provide a better guarantee of effectiveness. A compromise may nevertheless be found, since contract duration has been shown to have a negative effect on land-user participation in PES contracts (Bougherara & Ducos, 2006; Ruto & Garrod, 2009; Vaissière et al., 2018). Recent guidelines issued by the Rhône-Mediterranée-Corse Water Basin Agency in France[8] recommend the use of alternatives to PEvSA when transfer time exceeds 30 years, such as the conversion of farms to organic farming or the acquisition of land by public entities to ensure a full control over land-use.

Issues relating to the difficult observability of the effects of land-use decisions at the watershed level, and the impossibility of linking groundwater indicators to individual decisions, suggest the need for developing result-oriented payments based on intermediary results. However, we observe the overwhelming prevalence of action-oriented payments that ignore the conditionality criteria of PEvS programmes. New remote-sensing techniques may provide an opportunity for the future development of result-oriented schemes. These methods could generate indicators of the results of land-use decisions at low cost. High-resolution satellite image time series provided by Sentinel-1 and Sentinel-2 may be used in the future to evaluate land use change (Schulz et al., 2019), such as detecting the real development of cover crops on key dates[9] (Gao et al., 2020), which can then be used as a low-cost indicator of the compliance by farmers with PEvSA requirements.

Direct transactions between downstream EcSA users and upstream EvSA providers are seen only in the case of mineral-water PEvSA projects. In most other cases, intermediary institutions to ensure transactions are needed, either through NGOs, local government intuitions, water utilities or central government. Although government-led systems dominate in Europe, the present promotion of innovative PES programmes leads to the development of new and innovative intermediate institutions that may be promising in terms of flexibility, such as the Alli'hommes[10] initiative

[8] https://www.eaurmc.fr/jcms/pro_101439/fr/guide-technique-sdage-captages-eau-potable-prioritaires-aout-2020

[9] Cover crops, capturing excess nitrogen after the growing season, reduce nitrate flux in aquifers

[10] https://opera-connaissances.chambres-agriculture.fr/doc_num.php?explnum_id=150453

promoted by groups of farmers searching for potential ecosystem users to implement PEvS contracts. EcSA demand remains, however, weak due to a lack of understanding of the general public. Approaches based on the labelling of products generating EcSA, such as in the Kumamoto example, in Munich, or as in the case of the Catskill Mountain programme developed for improving the quality of surface water used for the drinking-water supply of New York City (Grolleau & McCann, 2012), are promising avenues to stimulate demand and secure the funding of PEvSA programmes.

Finally, evidence of the impact of payment of environmental services on actual ecosystem services related to aquifers remains very scattered. Some studies highlight the impact of modifying agricultural practice (Chabé-Ferret & Subervie, 2013; K. W. Jones et al., 2020; Kuhfuss & Subervie, 2018; Pufahl & Weiss, 2009; Reinhard & Linderhof, 2015; Wallander & Hand, 2011), but very limited evidence exists on the actual impact of PEvSA programmes on groundwater (Slabe-Erker et al., 2017). A scientific effort should therefore focus on evaluating the contribution of PEvSA programmes to ecosystem services related to aquifers. This would require the use of state-of-the-art impact-analysis methods, such as the ones used for evaluating the impact of the REDD+ PES programmes (Simonet et al., 2019), coupled with advanced hydrogeological modelling for predicting the effect on aquifers. These studies should be used for cost-effectiveness analysis, in order to compare the cost and impact of alternative programmes, including either preventive PES programmes, or curative water-treatment actions at the image of the Munich example (Grolleau & McCann, 2012). This type of approach, which has been very rarely implemented, would be particularly relevant for policy makers and can help building a case for PEvSA development.

To some extent, the challenges identified for PEvSA also apply to other types of PES programmes. Indeed, a 5-year timespan is insufficient for ensuring a sustainable impact on biodiversity conservation. For example, senescent wood must be maintained in forests over many years to ensure a significant impact on rhizomes and insect communities. There are also uncertainties between land-use change and biodiversity benefits, and the need for coordination at landscape scale for obtaining significant results. Upstream-downstream solidarity is also a major challenge for the conservation of surface water. We argue, however, that the specificity of PEvSA lies first in the magnitude of some of these challenges. Because of the uncertainty and complexity of hydrogeological processes, the link between land-use change and groundwater is particularly difficult to predict, and must rely on modelling with high uncertainties. The transfer time of water from surface to groundwater can be decades in many contexts. As mentioned before, 41% of the abstraction points with quality problems of the Rhone-Mediterranean-Corsica basin have over 25 years of transfer time. This pervasive problem thus needs particular attention in PEvSA contracts. We also believe that PEvSA face a unique combination of challenges, partly faced by all PES contracts, and that highlighting this combination is particularly relevant for the study and design of such programmes. From the same perspective, most recommendations for addressing these challenges were formulated for other contexts. Returning to the example of senescent wood, long-term contracts with a 30-year commitment of conservation of such wood were proposed to private landowners in Natura 2000 forest areas. Our contribution, here, has been to adapt these recommendations and compile them for the specific case of PEvSA.

Appendix 1: Detailed description of environmental services related to aquifers

Environmental services for protecting upstream ecosystems

The quality and quantity of water that flows in aquifers, conditioning the production of EcSA, largely depends on processes happening in upstream ecosystems. Human action can particularly alter this relationship through:

- Land Cover and Land Use. The nature of the land cover and land use affects recharge through different mechanisms. Areas covered with deep-rooted vegetation, such as forests, have lower groundwater recharge rates than areas of shallow-rooted vegetation, such as annual crops (Scanlon et al., 2005). Land use also affects hydro-physical soil properties, such as texture and porosity that may in turn influence runoff rates and recharge. Tillage and the reduction of organic matter, commonly observed with agricultural activity, generally leads to larger runoff rates than forested land. Deforestation, despite positively influencing the quantity of water, can also directly affect groundwater quality through an increase in nitrate (Favreau, 2002) and salinisation (Allison et al., 1990). Depending on the agro-ecological context, the importance of these phenomena may vary (Owuor et al., 2016).
- Pollutant and nutrient loads. Fertilizers (nitrogen and phosphorus), pesticides used in agriculture and nutrient loads resulting from animal farming are dissolved and transported to aquifers through groundwater recharge, thus altering their quality (Böhlke, 2002).

Environmental protection of upstream ecosystems thus mainly relate to LUDs that generate a positive impact on EcSA. Examples of LUDs are the conservation/creation of forest cover and natural areas to preserve the quality of water flow into the aquifers, or the use of agricultural systems (crop types and agricultural practices) that lead to the reduction of pesticides and nutrient loads flowing into aquifers.

Managed Aquifer Recharge can also be considered an environmental service of protection of upstream catchment, as it increases the availability of water in aquifers. In this case, land users, through specific practices such as the flooding of fields, increase aquifer recharge (Taniguchi et al., 2019).

Environmental services of sustainable groundwater management

Aquifer overexploitation for irrigation has led to the depletion of groundwater in many parts of the world (Wada et al., 2010). This depletion of aquifers affects their capacity for sustaining EcSA by reducing their capacity to supply freshwater for future agricultural and drinking-water use and by affecting the production of ecosystem services of downstream ecosystems dependant on aquifers (Scanlon et al., 2005). Implementing sustainable irrigation is thus one of the aspects covered by

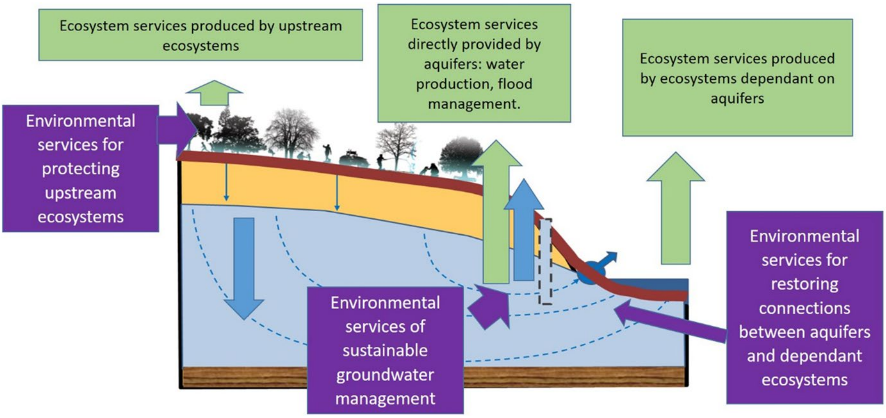

Fig. 1 Ecosystem services and environmental services related to aquifers (modified from Hérivaux & Marchal, 2019)

PEvSA. These may also include support for the adoption of irrigation practices that reduce water wasting, such as the adoption of optimal water irrigation (Cheviron et al., 2020), or the adoption of water-saving techniques such as drip-irrigation. The adoption of crops or varieties with reduced water needs is another possible objective of PEvSA programmes.

Environmental service for restoring connections between aquifers and dependant ecosystems

Restoring the connection between aquifers and dependant ecosystems can strengthen two EcSA: flood risk reduction through storing floodwater into aquifers, and the services generated by ecosystems dependant on aquifers. Actions such as floodplain restauration and/or the renaturation of rivers may generate these environmental services by favouring stream-groundwater exchange (Kasahara et al., 2009). Such actions are preferably implemented through land acquisition as they mainly require the permanent reconversion of land use. The use of PEvSA can also be considered when implementing temporary measures, such as the compensation of yield losses in flood plains reconnected to rivers (Guida et al., 2016). While this type of PEvSA may theoretically exist, we could not find concrete examples of their implementation.

We present our conceptualization of environmental services and ecosystem services in Fig. 1.

Code availability Not applicable.

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