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Valley-bottom wetland selection for water-quality preservation: how to deal with the absence of quantification of water-quality benefits?

Pierre Curmi¹, Mohamed Hilal², Elsa Martin^{2,*}, Virginie Piguet²

Abstract: We combine soil science and economics to provide an integrated framework of Valley-Bottom Wetland (VBW) selection criteria for surface water-quality preservation at the headwater watershed scale when there is no reliable method for quantifying water-quality benefits. We focus on a French agricultural landscape and more particularly on wet meadows. We implement a method of VBW identification based on topographic indices which use threshold values that are calibrated using field measurements. This identification criterion allows us to accurately identify both downstream and upstream VBWs. We then look for criteria with which to prioritize the VBWs identified for conservation purposes. We concentrate on budget-constrained cases and provide a procedure for estimating the cost of conservation for the VBWs. We finally show that it is very important (i) to simultaneously consider hydrogeomorphic and cost criteria for the selection in a budget constrained context and (ii) to go beyond the mean per hectare cost of conservation.

Keywords: Wetland conservation; Nutrient-retention function; Prioritizing criteria.

*Corresponding author:

E-mail address: elsa.martin@inra.fr

Postal address: 26, Bd Dr Petitjean, 21000 Dijon – FRANCE

¹Biogéosciences, AgroSup Dijon, CNRS, Univ. Bourgogne Franche-Comté, F-21000 Dijon, France

²CESAER, AgroSup Dijon, INRA, Univ. Bourgogne Franche-Comté, F-21000 Dijon, France

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1. Introduction

Wetlands provide several ecosystem services (Mitsch and Gosselink, 2000). Despite this, degradation of wetlands is widespread and restoration is needed (Bai *et al.*, 2013). The main source of wetland degradation is linked to the divergence between private interests and public benefits. Ando and Getzner (2006) show that there is a marked bias against conserving wetlands that are privately owned. Applied to agricultural interests, van Vuuren and Roy (1993) estimate private and social benefits from generic wetland conservation versus conversion to agriculture to show the need for wetland conservation policies in Canada. Heimlich *et al.* (1998) develop the same kind of argument for the U.S. De Laporte (2014) furthermore points out the effect of crop prices on wetland conversion in Canada whereas Van Kooten (1993) studies the effects of government agricultural support programs.

One of the well-studied services provided by wetlands is the improvement of water quality. For instance, Moshiri (1993) gives over an entire book to the impact of constructed wetlands on water quality. Verhoeven *et al.* (2006) concentrate on the functional role of small wetlands in watersheds where the main source of pollution is agriculture. They explain that river catchments where the landscape is mainly agricultural often have lower-order stream (located upstream in the hydrologic network) subcatchments, i.e. headwater watersheds, that are strongly influenced by runoff from agricultural land use. Mérot *et al.* (2009) furthermore explain that Valley-Bottom Wetlands (VBWs) in agricultural landscapes (wet meadows) are omitted from international (Ramsar), national, and regional wetland inventories because they are small and scattered across the rural landscape. However, they explain that VBWs considerably influence hydrology and water quality throughout the watershed area because they are located in the bottomlands of the headwater watershed. We will concentrate on these VBWs in agricultural landscapes that are mainly intermittent wet meadows.

Turner *et al.* (2000) recommend conducting integrated ecological-economic analysis for the question of wetland management and policy improvement. We focus on an agricultural landscape and address this question at a headwater watershed scale within a framework of integrated research by economists and soil scientists alike.

The first step is to locate VBWs. Following Mérot *et al.* (2003), we assume that the primary control on VBWs is geomorphological: it determines the hydraulic gradient and the presence of high soil water content in valley bottoms. Intermittent stagnant water thus induced between storm events transforms soil into hydric soil and enables the growth of vegetation that may be specific either to classical wetlands (hydrophilic species) or to agricultural land use (wet meadows). The consequence is that the identification of the latter cannot be based on classical remote sensing data that only help in identifying

hydrophilic species (Lunetta and Balogh, 1999; Mulder *et al.*, 2011). In other words, in works based on remote sensing data, the vegetation criterion is more important than the soil hydromorphy criterion, which is not the case for VBWs. More particularly, the first step in VBW identification is to locate what Mérot *et al.* (2003) call potential VBWs since they represent the maximal theoretical extension of VBWs. Potential VBWs are identified on a geomorphological basis (topography and parent material). Here soil science methods are helpful. We locate VBWs at the headwater watershed scale based on seminal topographic wetness indices that were developed by Beven and Kirkby (1979). Such indices are used for predicting VBWs in Europe (Mérot *et al.*, 2003) and in France (Berthier *et al.*, 2014), taking into account climatic conditions. At the headwater watershed scale within an administrative region, climate variability is not sufficient, and as such, we ignore it. Contrary to Berthier *et al.* (2014), who determine national threshold values of topographic indices based on the stratification of hydroecoregions, we calibrate local threshold values based on field measurements. More generally, local threshold values are particularly adapted to headwater watersheds characterized by heterogeneous soil surface permeability where the climato-topographic index is proved to fail to predict wetland location (Mérot *et al.*, 2003; Berthier *et al.*, 2014). This local calibration enables us to take permeability into account when computing indices, much as was done in the seminal proposition by Beven and Kirkby (1979).

Once potential VBWs have been located, the second step is to evaluate their capacity to improve or secure a certain water quality. Yang and Weersink (2004) use a hydrologic model (the annualized agricultural nonpoint source pollution model) to examine land retirement targeting for establishing buffers connected to the river. The advantage of such a hydrological model is that it enables a precise measurement of water quality, taking into account several factors such as the size of the buffer, the inflow of pollutants, surface flows, etc. The disadvantage is that it needs a lot of precise data that are not always available (agricultural practices or water bodies for instance) and that it differs from reality since it remains a model. Yang and Weersink's (2004) study was applied to a watershed in Canada. As stressed by Mérot *et al.* (2009), in Europe, the interest in wetlands is new compared with North America. The consequence is that such hydrological models are not well-developed and that water agencies are far from being able to use them, at least in France. As a consequence, we argue that it is very much worth developing easily implementable methods to help them select wetlands in an effective way when there is no reliable method of quantifying water-quality benefits. Following Mérot *et al.* (2003), we will approximate the capacity of VBWs to improve or secure a certain water quality based on a qualitative classification that can be derived from the literature and that we will sum up in the method section.

According to Lavoux *et al.* (2013), water agencies in France spent €58 million on purchasing 13,426 ha of wetlands from 2009 to 2012.ⁱ A further €2.5 million went into the purchase and management of land for the purpose of water-quality preservation between 2002 and 2011 within the framework of a sensitive natural spaces policy (METL, 2011). The small amount of financial capital involved raises questions regarding the prioritization of the wetlands to be selected first for conservation purposes. Literature on biodiversity conservation shows that, in a world of limited budgets, consideration of the costs of preservation in the prioritizing procedure enables an increase in conserved biodiversity (Naidoo *et al.*, 2006; Newburn *et al.*, 2005). We propose to test this idea in the case of wetland conservation for water-quality preservation. Once potential VBWs have been located and their capacity to improve or secure water quality evaluated, the third step is to estimate the cost of their conservation.

To the best of our knowledge, the literature on wetland prioritization focuses mainly on restoration, rather than on conservation (see, for instance, Darwiche-Criado *et al.*, 2017). One exception is the work by De Laporte *et al.* (2010) who propose a cost-effective prioritization procedure based on integrated economic and hydrologic modeling. However, contrary to our focus on VBWs, they concentrate on generic wetlands located without consideration of their soil characteristics (a small number of wetlands were investigated based on an inventory from a water agency). Furthermore, they compute returns to alternative land uses in order to estimate the cost of conservation; it is an opportunity cost. For data availability reasons, we concentrate instead on the purchase costs of VBWs, i.e. market prices of agricultural land. To do so, we follow Newburn *et al.* (2006) in implementing a hedonic price method.

To sum up, our main contribution to the literature is to provide an integrated framework of VBW conservation strategy, involving both economists and soil scientists, that could be easily implemented by a local agency in charge of water-quality management of a headwater watershed. On the one hand, our contribution with respect to the water resource economics literature is to provide an analysis regarding the trade-offs between decreased costs and increased effectiveness of different strategies of VBW prioritization when there is no reliable method to quantify water-quality benefits. On the other hand, our contribution to the soil science literature is to provide a method of VBW identification based on soil hydromorphy for headwater watersheds characterized by heterogeneous soil surface permeability where it is proved that the climato-topographic index fails to predict wetland location.

The next section describes the data and methods used in this study. Then, we present the results from the estimation of the cost of agricultural lands, followed by the results from the classification of VBWs with respect to their potential in terms of water-quality preservation. Afterwards, we analyze the

ⁱ <http://www.zones-humides.org/agir/plans-et-programmes/acquisition-de-20-000-ha>

trade-offs between decreased costs and increased effectiveness of different strategies of VBW prioritization. The final section sets out the conclusions.

2. Materials and methods

2.1. Headwater watershed selection and characterization

We perform the analysis on two French agricultural headwater watersheds: the Brenne and the Armançon which are located in the administrative division of Côte-d'Or (equivalent of NUTSⁱⁱ 3 subdivision, 8,800 km² and 533,000 inhabitants), northeast France (see Figure 1).ⁱⁱⁱ This area has a continental climate.

Both watersheds have natural and semi-natural land cover (urbanization cover is approximately 2.5%). This land cover is mainly agricultural and is composed of meadows and cereals (forest cover is 14% in the Armançon and 25% in the Brenne watersheds).^{iv} More particularly, the Brenne watershed covers 781 km², 30.8% of which is meadowland and 22.2% cereal crops. There are 20,883 agricultural plots. The mean concentration of nitrate observed at the outlet is 19.7 mg/L; the mean flow is 9.2 m³/s; and the mean flux of nitrate is 20.8 kg/km²/day.^v The Armançon watershed measures 333 km², 45.6% of which is given over to meadows and 17.6% to cereals. There are 11,892 agricultural plots. The mean concentration of nitrate observed at the outlet is 16.4 mg/L; the mean flow is 2.5 m³/s; and the mean flux of nitrate is 10.1 kg/km²/day.

We specifically chose these headwater watersheds for data availability reasons and because they are characterized by different parent material permeability values which may mean that these VBWs differ in terms of their hydrological functioning. The parent material of the Brenne watershed is mainly (>50%) permeable limestone^{vi} whereas for the Armançon it is mainly (>50%) composed of impermeable marls. In both watersheds, the most common texture of soils is clay and clay mixed with silt.^{vii}

ⁱⁱ The nomenclature of territorial units (NUTS) for statistics classification is a hierarchical system for dividing up the economic or administrative territory of the European Union.

ⁱⁱⁱ Both headwater watersheds are hydrologically connected downstream (North of the map in Figure 1) despite what appears in Figure 1 because we delimited both watersheds with respect to water monitoring stations upstream from their confluence.

^{iv} Source: The French National Institute of Geographic and Forest Information - French topographic database, Agency for Services and Payment (France) and Integrated Administration and Control System (European Union) – Land Parcel Identification System (2006–2009).

^v Source: Seine-Normandie Water Agency – French surface water quality database (1994–2010) and Ministry for the Ecological and Inclusive Transition – French hydrometric database.

^{vi} Source: The French Geological Survey – French geological database.

^{vii} Source: The French Soils Scientific Interest Group – French soil database.

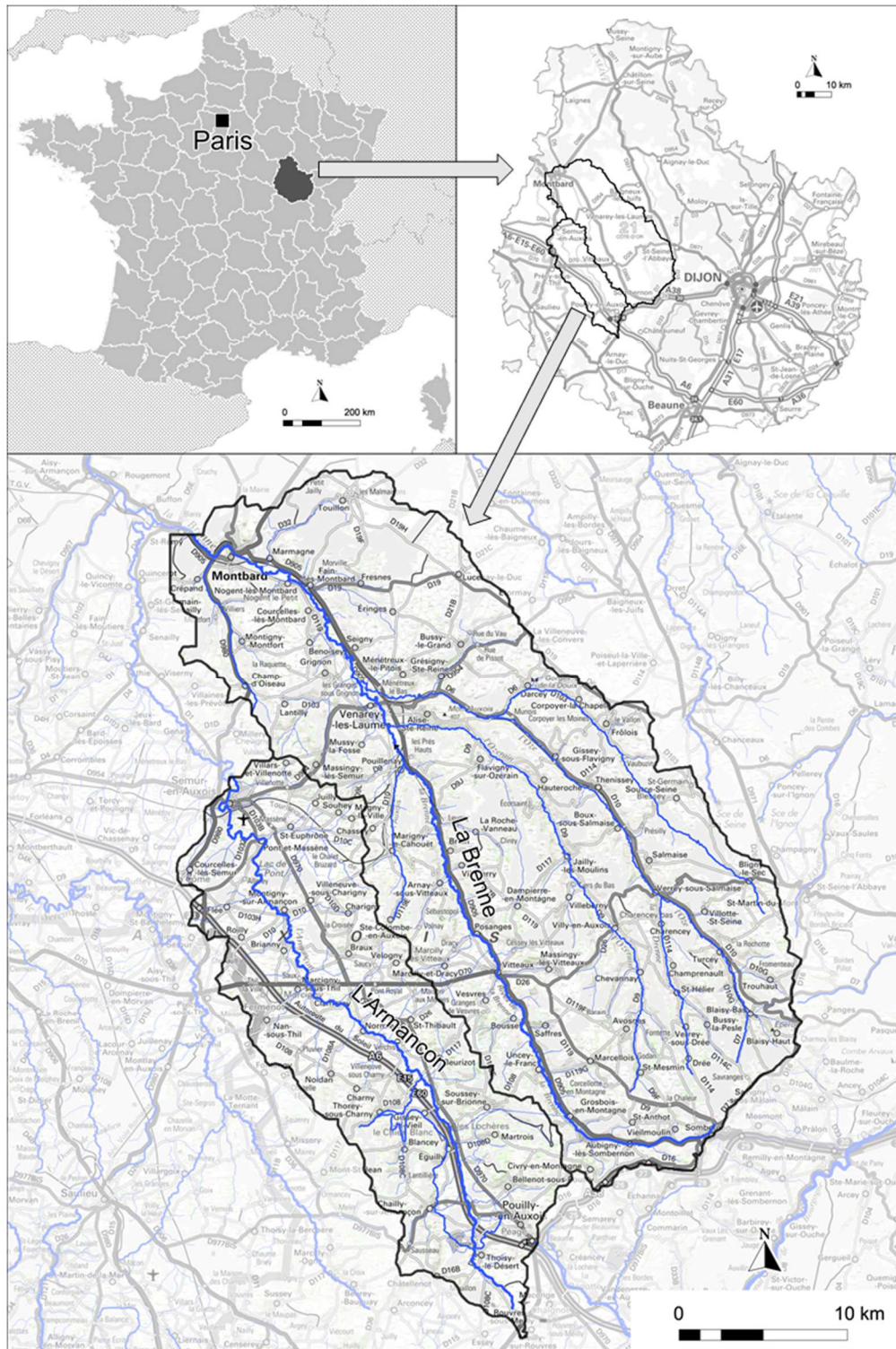


Figure 1: Study area – the Brenne and Armançon watersheds

(bounding coordinates - Lambert93, RGF 93: N 6731000, W 796800, E 834400, S 6679000)

Hydrologically, the Brenne is a rounded watershed that is characterized by 780 km of rivers, among which 87% have a Strahler order^{viii} lower than 4 (i.e. they are located upstream in the watershed), and

^{viii} The Strahler order is a standard stream classification proposed by Strahler (1952).

13% are 4th order or higher, (i.e. are located downstream) (see Figure 2).^{ix} The Armançon is a relatively elongate watershed that is characterized by 376 km of rivers, among which 90% have a Strahler order lower than 4 and 10% are higher than or equal to 4. The main river does not exceed 5th order in the area under study.

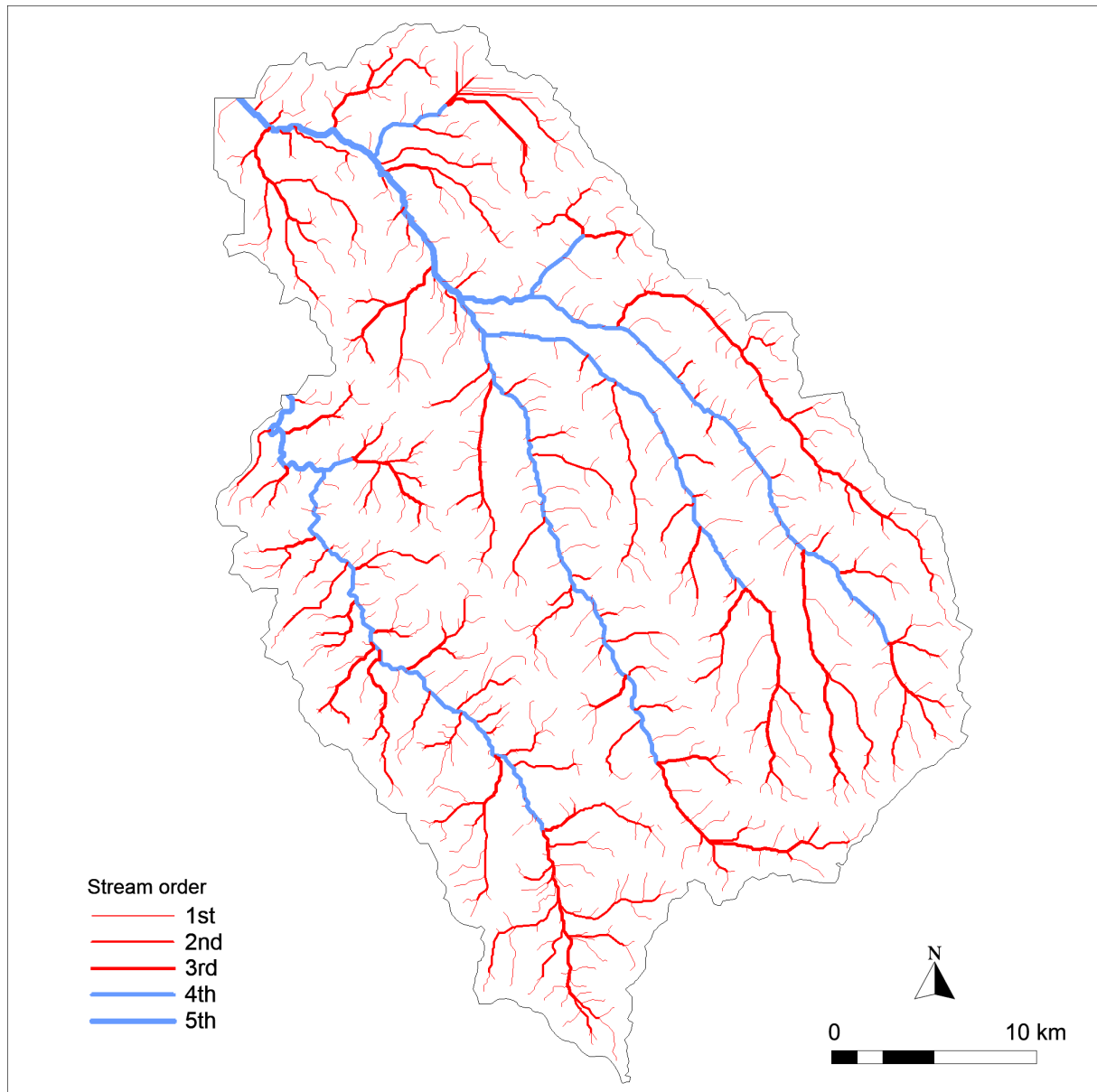


Figure 2: Stream orders of the Armançon (south-west) and Brenne (north-east) river networks

2.2. VBW location: soil science materials and methods

To prioritize VBWs for conservation purposes, the first step is to locate them. To do so, either of two main criteria can be used: vegetation or soil hydromorphy. For instance, the French water statute of

^{ix} Source: The French National Institute of Geographic and Forest Information – French topographic database.

1992 defines VBWs mainly with respect to vegetation, and it is a statutory decree of 2007 that adds soil hydromorphy to the definition. Here, we propose to concentrate on the soil hydromorphy criterion, which seems more challenging, especially with respect to French legislation and to VBWs. French standard soil surveys provide an approximation of soil hydromorphy. However, an accurate description of the spatial distribution of soil hydromorphy requires supplementary mapping techniques because of the methodological and economic constraints of standard soil survey procedures (Chaplot *et al.*, 2000; Chaplot *et al.*, 2003). The method used for identifying VBWs consists of two steps: the first step is to compute topographic indices, and the second to find local threshold values of these indices (i.e., values for which we can predict the presence of a VBW).

First, to compute topographic indices, we begin with the seminal proposal of Beven and Kirkby (1979) by computing a topographic wetness index, denoted IBK, based on the concept of contributing area. To do so, we use a data elevation model with 25 m resolution provided by the French National Institute of Geographic and Forest Information (IGN). Furthermore, we follow the methods of Mourier *et al.* (2008) who recommend computing different topographic indices according to stream order. To do so, we compute different indices according to the Strahler order. For streams with Strahler orders lower than 4 (located upstream in the watershed), denoted with the subscript ls for low Strahler, we compute the index proposed by Mérot *et al.* (1995):

$$IBK_{ls} = \ln\left(\frac{A}{\tan\alpha}\right)$$

where A denotes the drainage area per unit contour length and $\tan\alpha$ the local slope angle. For streams with Strahler orders greater than or equal to 4 (located downstream in the watershed), denoted with the subscript hs for high Strahler, we compute the index proposed by Crave and Gascuel-Oudou (1997):

$$IBK_{hs} = \ln\left(\frac{A}{\tan\beta}\right)$$

where $\tan\beta$ denotes the downslope gradient. This hydraulic gradient is equal to the ratio of the vertical over the horizontal distances between the sample point and the channel network.

Second, we determine threshold value of these indices. To establish these thresholds, we make field measurements based on transects. The transects are located where the BK index decreases as gradually as possible from the stream to the slope. Furthermore, transects are representative of the regional geology and the Strahler order. The permeability of the parent material is crucial in identifying VBWs. Beven and Kirkby (1979) recommended considering transmissivity. The Brenne and Armançon watersheds correspond to two different geological settings, the former permeable and the latter

impermeable. We locate transects based on low and high Strahler orders. Ultimately, we test 20 transects (with different combinations of parent material and Strahler order). In the field, soil hydromorphic features and the measurement of iron-manganese concretions (D'Amore *et al.*, 2004) are identified on the boundary between well drained and poorly drained places to determine the value of the threshold from which a VBW can be predicted.

2.3. VBW qualitative classification for water-quality preservation: some useful results from the environmental science literature

Once located, the second step in VBW prioritization is to select the VBWs that best preserve water quality. The nutrient-retention function of wetlands is now well known (Mitsch and Gosselink, 2000), and as such, we focus on this function. However, it remains difficult to precisely quantify nutrient retention for each potential VBW. To accommodate such difficulties, Mérot *et al.* (2006) proposed a theoretical qualitative analysis of potential, existing, and effective wetlands (PEEW) that is summed up in Figure 3.

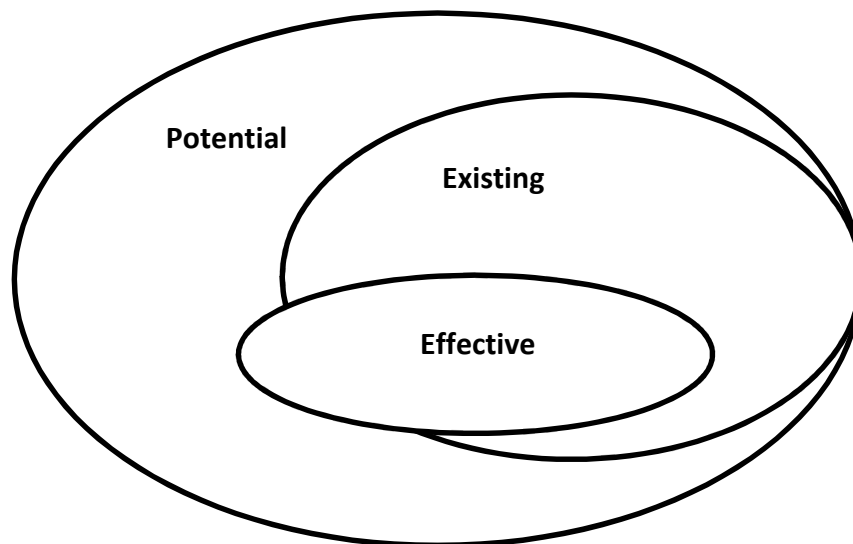


Figure 3: The PEEW (potential, existing, effective wetlands) approach (source: Mérot *et al.* 2006)

Topographic wetness indices indicate potential VBWs. They correspond either to agricultural or forest land-use. Since agriculture poses a greater threat of degradation than forestry (Heimlich *et al.*, 1998), we focus on VBW conservation of agricultural lands. Drainage then helps to distinguish between potential and existing VBWs. This information is not easy to obtain at the plot scale. Mérot *et al.* (2006) approximate drainage by considering that cultivated lands are drained whereas meadows are not. We will make the same assumption. In the classification proposed by Mérot *et al.* (2006), potential VBWs minus existing VBWs designates degraded VBWs. When focusing on the effectiveness with respect to

a specific function, some VBWs have the potential to become effective again if restored. Here, we concentrate on existing VBWs because degraded VBWs require a valuation of their restoration costs in addition to their purchase cost.

Hydrogeomorphic criteria are helpful (Mitsch and Gosselink, 2000) in identifying different types of VBWs with respect to the effectiveness of their nutrient-retention function (see Figure 4). First, riparian VBWs (i.e. those connected to the river) are crucial for nutrient retention because of their roles as buffers (Pinay and Decamps, 1988; Ockenden *et al.*, 2014). As such, connected VBWs are more effective than unconnected VBWs. Second, parent material plays a crucial role: VBWs on permeable parent material are more effective than those on impermeable parent material because they induce more exchanges of water between the stream and the riparian zone (Grimaldi and Chaplot, 2000).

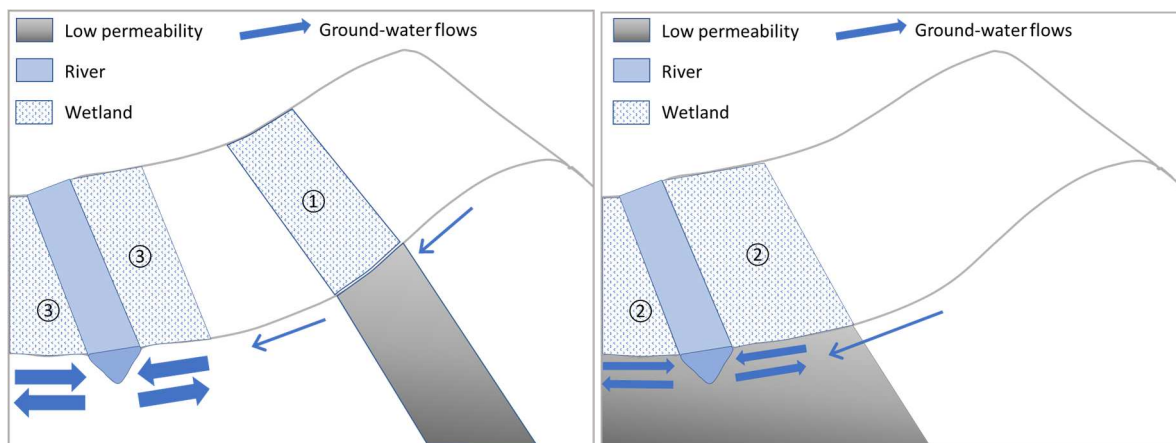


Figure 4: Classification of valley-bottom wetlands (VBW) with respect to effectiveness. (1) unconnected; (2) connected low permeability; (3) connected high permeability.

Third, Montreuil and Mérot (2006) and Montreuil *et al.* (2010, 2011) show that VBWs located upstream (low Strahler orders) are crucial for nutrient retention. In the Brenne and Armançon watersheds, upstream VBWs are located next to agricultural runoffs whereas downstream (high Strahler orders), agricultural plots are fewer and mainly located at the bottom of the valley, because the slopes are steeper and more difficult to cultivate as soon as one moves away from the river. Furthermore, it is a well-established result that effectiveness is higher upstream than downstream for periods of low discharge (Wollheim *et al.*, 2008). This can be explained by the increase in residence time (Puckett *et al.*, 2008) which favors oxygen consumption and denitrification, as well by the fact that the hydrographic network is denser upstream than downstream which increases the area of contact between streams and wetlands (Howarth, 1996).

Based on the previous elements, we propose to adopt the following hierarchy for the different types of VBWs with respect to their effectiveness in the Brenne and Armançon watersheds:

Connected_upstream_permeable > Connected_upstream_impermeable > Connected_downstream >
Unconnected

2.4. Estimating the purchase cost of VBWs: economic materials and methods

The method for estimating the purchase cost of potential VBWs follows Hilal *et al.* (2016) and consists of two steps. The first step is related to the estimation of a price function for agricultural land sold in the market, based on the observation of real-estate transactions. We define agricultural land as either a field or a meadow, excluding vineyards, orchards, and forests because we assume that additional information is needed in order to estimate the latter land uses. The second step involves predicting the price of agricultural land in 2008. For this purpose, we use a land-use layer for that year created in Hilal *et al.* (2016). The land under consideration at this step is not necessarily sold in the market, which may be the case for potential VBWs. The predictions are based on the estimation results obtained in the first step. Because the land market is more widespread than a watershed, we concentrate only on the Côte-d'Or administrative division which is the scale at which companies for agricultural real-estate management operate.

First, we begin by estimating a hedonic price function of agricultural lands:

$$\ln p_i = \alpha + \beta l_i + \gamma t_i + \delta s_i + \mu c_i + \varepsilon_i$$

where p_i denotes the price of the plot i ; l_i the location characteristics of the plot; t_i its topographic characteristics; s_i its soil properties; c_i denotes control variables; and ε_i is the error term. Table App-1 summarizes the variables included in the regression. Qualitative properties were put into quantitative form through dummy variables. Quantitative variables that exhibit non-linear relations with respect to the price were cut according to thresholds that were found by iteration, beginning with the aggregations that have the smallest impact on the adjusted R^2 . This model is an adaptation of the one proposed by Hilal *et al.* (2016): we use the same data but a different model that we consider to be more appropriate for our headwater watershed analysis.

The seminal model is adapted in three ways. First, we simplify soil properties and location characteristics to reduce the number of explanatory variables. Second, we introduce the percentage of the plots under the jurisdiction of a river management scheme because it is linked to the wetland selection problem for water-quality preservation. Third, we introduce a new control (the percentage of the plot in either one or the other watershed) to test whether this model is appropriate for the watershed under study. Finally, location characteristics are measured by the Euclidian distance to the town hall, travel distance to the intermediate-level municipality that provides shops, facilities and

public and private services, a dummy variable that indicates if the municipality is also the regional capital (Dijon), and percentage of the plot covered by a river management scheme. Topographic characteristics are measured by area, altitude, and slope. Soil properties are measured by determining textures (very fine, fine, medium, and coarse). Control variables include the percentage of the plot in either the Brenne or Armançon watershed, the year of the transaction, and whether the farmer is the purchaser or not. Land cover is classified as meadow or arable land.

To estimate this function, we use data that were constructed and described in Hilal *et al.* (2016). More specifically, we focus on 6,477 transactions between 1992 and 2008 in Côte-d'Or (see Table App-2 in Appendix 1 for the descriptive statistics of this sample). The estimation procedure is an Ordinary Least Squares (OLS) procedure, where we produce standard errors that are robust to heteroscedasticity and to intra-municipal spatial autocorrelation.^x To do so, we compute cluster-robust standard errors (Cameron and Trivedi, 2010) using a cluster for each municipality (667 in our case).

Second, we use the estimated coefficient of the first steps to predict the price of the 42,189 undeveloped agricultural plots of the watersheds under study (see Table App-3 in Appendix 1 for the descriptive statistics of this sample). The presence of heteroscedasticity induces some specificity in the prediction procedure (for more details, see Hilal *et al.*, 2016). More specifically, we confirm that the Meulenbergh (1965) proposal is the most appropriate predictor that was proposed in Hilal *et al.* (2016), according to the computation of a correlation coefficient with the real price and standard Mean Absolute Error (MAE) and Root Mean Squared Error (RMSE) indicators.^{xi} Finally, we introduce a corrective term such that the predicted price has the following form:

$$p_i = \exp(\hat{\alpha} + \hat{\beta}l_i + \hat{\gamma}t_i + \hat{\delta}s_i + \hat{\mu}c_i + 0.5(1 - \vartheta_i)\hat{\sigma}^2)$$

where $\vartheta_i = x_i(X'X)^{-1}x_i'$ with X the matrix of explanatory variables and x_i the i_{th} row of X ; and σ^2 denotes the variance of the error term.

3. Purchasing cost of agricultural land in the Armançon and Brenne watersheds

^x We run a White's test (White, 1980) leading us to reject the homoscedasticity assumption of the residuals and a Moran's I test (Moran, 1950) considering intra-municipal proximity to deduce the presence of spatial autocorrelation.

^{xi} MAE is the average of the absolute differences between prediction and actual observation. RMSE is the square root of the average of squared differences between prediction and actual observation. MAE and RMSE are among the most common indices of predictive accuracy (Fair, 1984).

The results of the hedonic price function estimation are reported in Appendix 2 (Table App-4 provides the estimations with our model and Table App-5 the estimations from Hilal *et al.* (2016)). The adjusted R^2 increased with respect to the estimations of Hilal *et al.* (2016), from 71.15% to 71.87%. Hence, the model used for predicting the purchase cost of VBWs explains 71.87% of the variance in the log of the price. The absence of statistical significance in the estimated coefficients associated with the location of the plots in the Brenne or Armançon watersheds shows that our estimated model of the land market of Côte-d'Or is suitable for those watersheds.

The estimated coefficients associated with the presence of a river management scheme are of great interest. Indeed, some coefficients are positive and others negative. More specifically, the fact that an agricultural plot is located in the jurisdiction of the Armançon or Arroux management schemes lowers its price. In contrast, we find that the location of an agricultural plot in the jurisdiction of the Tille or Vouge management schemes increases its price. This result is linked to the fact that the Armançon and Arroux management schemes are restrictive for agricultural activities because their main goal is water-quality management. The Tille and Vouge management schemes are concerned with water quantity management because of urbanization. They can also be restrictive for agricultural activities in the short term, but in the long term, as noted by Cavailhès and Wavresky (2003), expected urbanization fully determines agricultural land prices. In the long term, the expected increase in water-resource availability makes urbanization possible and, therefore, raises agricultural land prices because of conversion possibilities. Figure 5 illustrates this point. Indeed red areas, representing the highest prices, correspond to agricultural plots located within towns or hamlets; orange areas correspond to farmland near roads in the valleys; yellow areas indicate plots on the outskirts of the towns or hamlets, and blue areas are areas with very low population density.

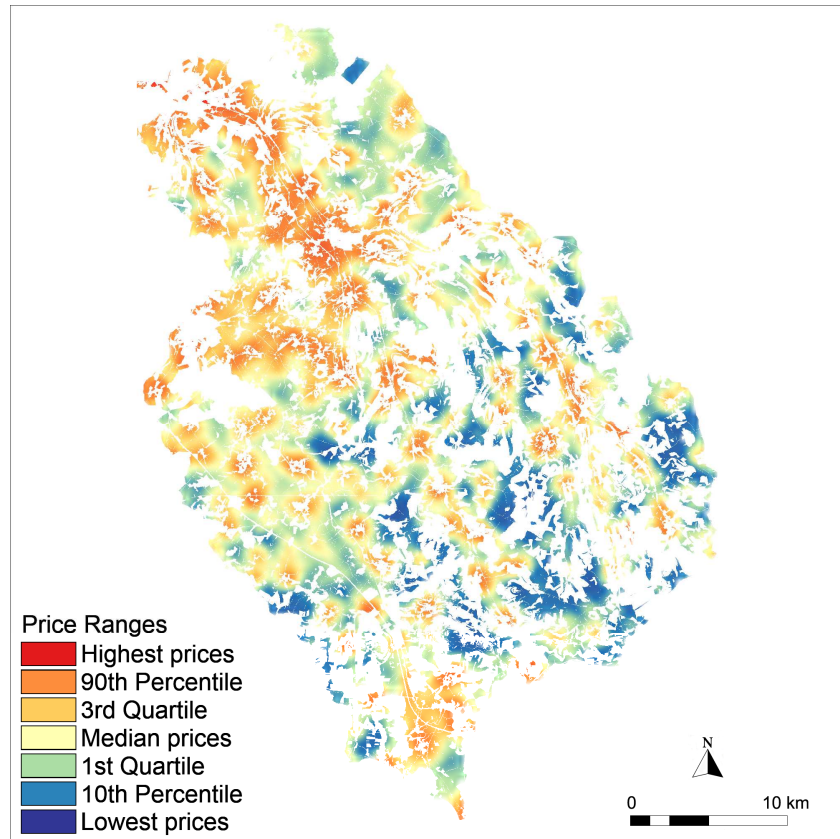


Figure 5: Spatial variation in the purchasing cost of agricultural land

4. VBW location and hydrogeomorphic prioritization at the headwater watershed scale

The threshold values of topographic wetness indices obtained from field measurements described in more details in the second step of the soil science materials and method section are reported in Appendix 3 (Table App-6). They differ by Strahler order and the type of parent material. They allow us to predict potential VBW locations. More specifically, we predict 33.37% of potential VBWs in the Armançon watershed (over the 333 km² area of the watershed) and 10.71% in the Brenne watershed (over 781 km²).

When comparing the location of potential VBWs provided by topographic indices with the locations provided by hydromorphy from soil mapping units (Figures 6a and 6b), it is apparent that topographic indices locate small VBWs in the Brenne watershed, whereas soil mapping units do not. Furthermore, topographic indices increase the precision of VBW locations whereas soil mapping units provide broad predictions only, especially in the Armançon watershed.

Another interesting comparison is between the locations of potential VBWs predicted at a local scale and the locations predicted at national scale, as discussed in Berthier *et al.* (2014) (Figures 6a and 6c). Local predictions provide more precise locations than national predictions. More specifically, local predictions can either reduce (Brenne) or increase (Armançon) the extension of VBWs obtained from national predictions. MEDDE, GIS Sol (2014) statistically tested the validity of the predictions proposed in Berthier *et al.* (2014). They stress that the quality of their VBW predictions is very low for parent material such as those that characterize the Brenne and Armançon watersheds. This emphasizes the relevance of our method for predictions at a local scale.

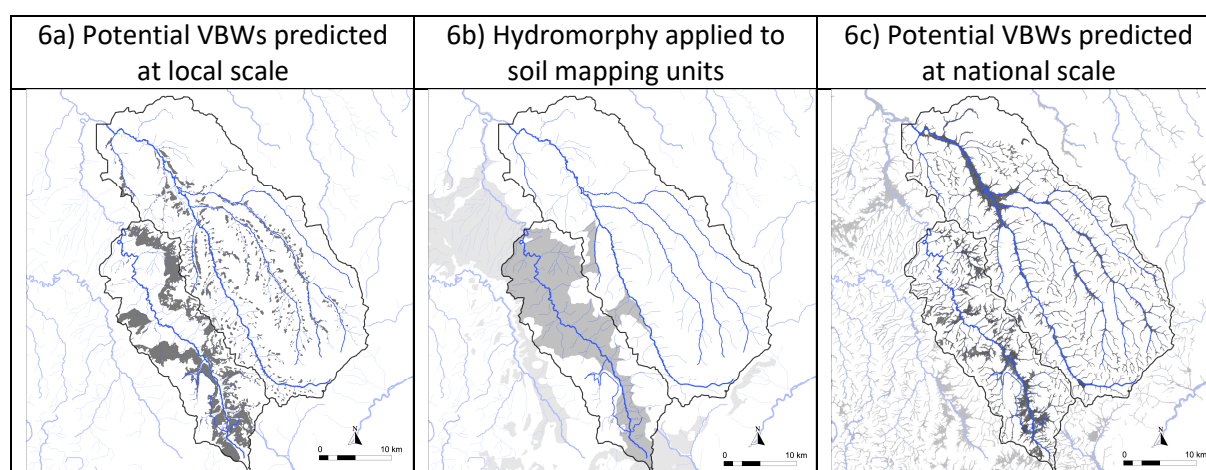


Figure 6: A comparison of three different approaches for mapping VBWs

Let us now move to the prioritizing procedure of these potential VBWs for conservation purposes. First, we focus on agricultural land-use. In the Armançon watershed, 66.4% of potential VBWs (101 km²)^{xii} are located on agricultural land. This is the case for 55% of VBWs (66 km²) in the Brenne watershed. Second, following the functional analysis proposed by Mérot *et al.* (2006), we remove cultivated lands to obtain existing VBWs. Approximately one quarter of potential agricultural VBWs are removed from each watershed. This results in 5,088 ha of remaining existing VBWs in agricultural use in the Armançon watershed and 2,770 ha in the Brenne watershed. Third, we differentiate the remaining existing VBWs according to the hydrogeomorphic criteria summed up in Figure 4. This includes whether they are connected or unconnected to a river, connected upstream or downstream, and connected upstream with high or low permeability.

Table 1 and Figure 7 summarize the variation obtained within each watershed. The two watersheds have very different profiles with respect to their VBWs. The ratio of unconnected VBWs to connected VBWs is higher in the Armançon watershed than in the Brenne watershed. Among the connected

^{xii} The difference between potential VBWs resulting from the data elevation model and potential VBWs considered at the broader scale of the plot is linked to the change of scale of the analysis.

VBWs, the Armançon has more upstream VBWs than downstream VBWs, and the reverse is true in the Brenne watershed. Among upstream-connected VBWs, both watersheds have more VBWs with low-permeability parent material.

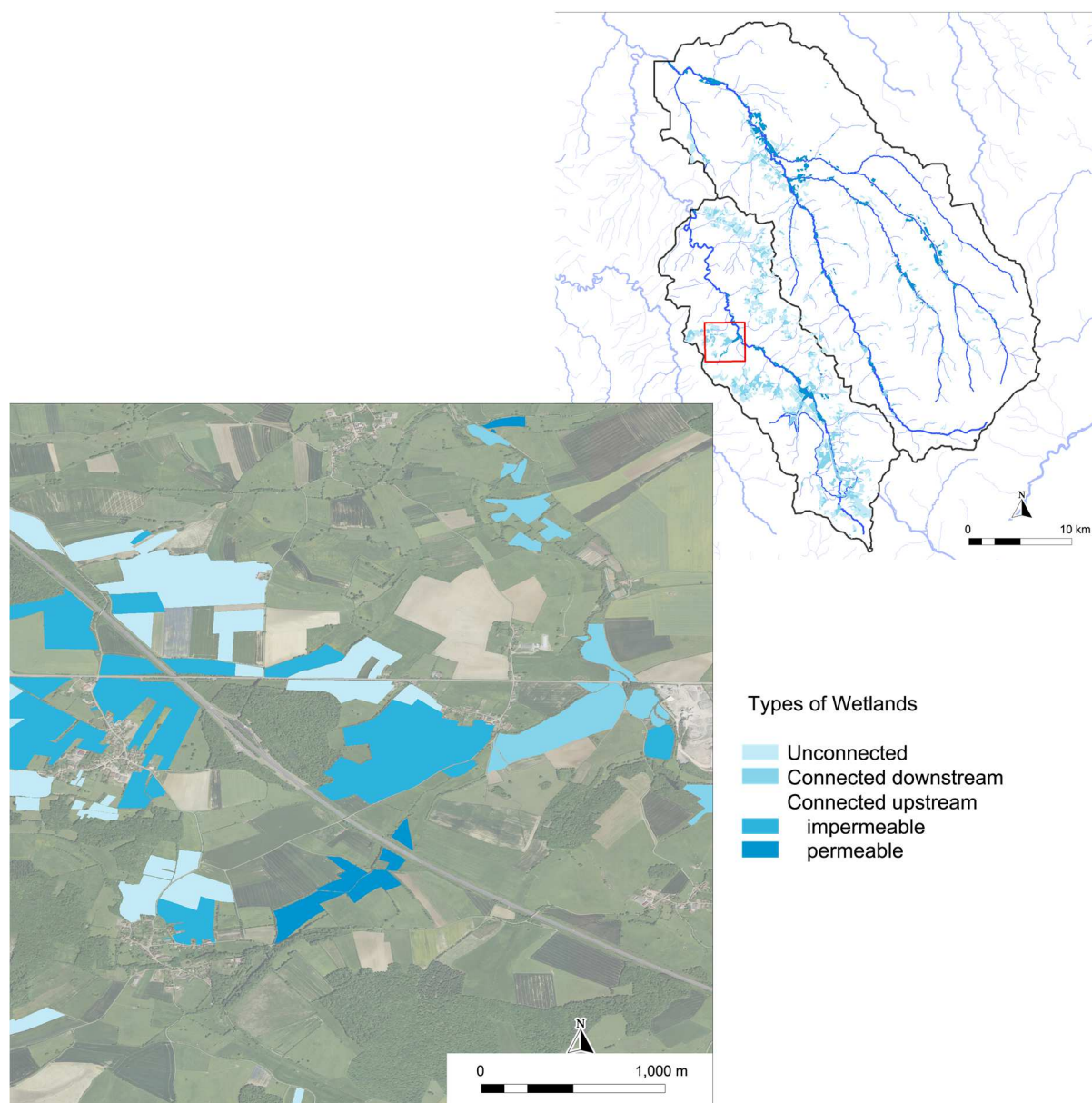


Figure 7: Location of the four types of VBWs

Table 1: Distribution of existing VBWs based on hydrogeomorphic criteria

| Types of VBW | Armançon | | Brenne | |
|--------------|-----------------|-----------|-----------------|-----------|
| | Number of plots | Area (ha) | Number of plots | Area (ha) |

| | | | | |
|--------------------------------|-------|-------|-------|-------|
| Unconnected | 1,692 | 2,871 | 836 | 1,044 |
| Connected | 1,119 | 2,217 | 1,342 | 1,725 |
| Connected downstream | 116 | 310 | 767 | 1,148 |
| Connected upstream | 1,003 | 1,907 | 575 | 578 |
| Connected upstream impermeable | 958 | 1,874 | 534 | 567 |
| Connected upstream permeable | 45 | 33 | 41 | 11 |

5. Trade-offs between decreased cost and increased effectiveness of VBW conservation

Figure 5 was generated from the predicted prices of all agricultural plots of the Armançon and Brenne watersheds. We now focus on the prices of existing VBWs that are used for agriculture. Table 2 summarizes the price, both in total and on a per-hectare basis, in each watershed. An agency willing to purchase agricultural VBWs in both the Armançon and Brenne watersheds would have to pay €24.5 million, which represents nearly one-third of the budget for VBW purchases by French water agencies between 2009 and 2012. Approximately 60% of this budget would be dedicated to the Armançon watershed. The global amount of €24.5 million corresponds to a mean unit cost of €3,109/ha – €2,881/ha for the Armançon watershed and €3,527/ha for the Brenne watershed. VBWs in the Armançon watershed are cheaper than those in the Brenne watershed, but there are more of them.

Table 2: Prices of existing VBWs according to hydrogeomorphic criteria

| | Armançon | | Brenne | | Both watersheds | |
|-------------|-----------|-------------|-----------|-------------|-----------------|-------------|
| | Total (€) | Mean (€/ha) | Total (€) | Mean (€/ha) | Total (€) | Mean (€/ha) |
| Unconnected | 8,173,692 | 2,847 | 3,250,157 | 3,112 | 11,423,849 | 2,917 |
| Connected | 6,482,668 | 2,924 | 6,518,961 | 3,779 | 13,001,629 | 3,298 |
| Downstream | 806,357 | 2,600 | 4,312,916 | 3,758 | 5,119,273 | 3,512 |
| Upstream | 5,676,311 | 2,977 | 2,206,045 | 3,820 | 7,882,356 | 3,173 |
| Impermeable | 5,576,189 | 2,976 | 2,161,484 | 3,813 | 7,737,673 | 3,170 |
| Permeable | 100,123 | 3,039 | 44,561 | 4,192 | 144,683 | 3,320 |

The amounts of money involved are so high that it is unavoidable to prioritize the VBWs that must be purchased first. Let us first consider an agency that uses an economic criterion alone for selection: this

agency selects the least cost VBW first. Table 3 summarizes the type of VBW selected by such a procedure when the budget earmarked for conservation stands at €100,000. VBWs connected upstream with high permeability are not conserved whichever watershed the budget is allocated to: the Armançon, the Brenne, or both. When the €100,000 are spent exclusively on the Brenne or on both watersheds, VBWs connected downstream are not conserved. Tables App-7 to App-10 yield the same results as Table 3 for different budgets. We see that all types of VBW are selected in both watersheds and in the Armançon only for a budget of €500,000 and that this is the case in the Brenne only for a budget of €5 million.

Table 3: VBWs selected in the least-cost prioritization process with a budget of €100,000

| | Armançon | | | Brenne | | | Both | | |
|----------------------|----------------|-----------|-----------|----------------|-----------|-----------|----------------|-----------|-----------|
| | Cost (€) | Number | Area (ha) | Cost (€) | Number | Area (ha) | Cost (€) | Number | Area |
| Unconnected | 97,096 | 19 | 59 | 96,783 | 12 | 61 | 98,696 | 14 | 64 |
| Connected downstream | 2,217 | 1 | 1 | - | - | - | - | - | - |
| Upstream impermeable | 687 | 1 | 0* | 3,217 | 2 | 2 | 1,304 | 1 | 1 |
| Upstream permeable | - | - | - | - | - | - | - | - | - |
| Total | 100,000 | 21 | 61 | 100,000 | 14 | 63 | 100,000 | 15 | 65 |

*The areas are not equal to 0 ha: they are less than 1 ha but more than 0 ha.

Let us then consider an agency that operates in a cost-effective way, i.e. it selects VBWs based on the prioritization scale defined by the qualitative classification presented before, i.e. from the bottom of Table 2 to the top, by least cost. The results of such a selection are presented in Table 4. The main difference with respect to the previous prioritization process is that VBWs connected upstream with high permeability are the only type of VBWs to be selected when the budget of €100,000 is either spent on the Armançon watershed exclusively or on both watersheds. When such a budget is spent exclusively on the Brenne watershed, some VBWs connected upstream with low permeability are also selected. While the area is lower, the number of discrete wetland units preserved is higher than in Table 3, which may have additional water quality benefits since bigger wetlands are not always better in water quality (De Laporte et al., 2010).

Table App-11 to App-14 provides the same results as Table 4 for different budgets. We see that even for a budget of €10 million, not all types of VBWs are selected when spent on both watersheds since no unconnected VBWs are selected in this specific case. This means that the cost-effective prioritization process favors more effective but expensive VBWs than the least-cost prioritization process.

Table 4: VBWs selected in the cost-effective prioritization process with a budget of €100,000

| | Armançon | | | Brenne | | | Both | | |
|----------------------|----------------|-----------|-----------|----------------|-----------|-----------|----------------|-----------|-----------|
| | Cost (€) | Number | Area (ha) | Cost (€) | Number | Area (ha) | Cost (€) | Number | Area |
| Unconnected | - | - | - | - | - | - | - | - | - |
| Connected downstream | - | - | - | - | - | - | - | - | - |
| Upstream impermeable | - | - | - | 55,439 | 20 | 28 | - | - | - |
| Upstream permeable | 100,000 | 45 | 33 | 44,561 | 41 | 11 | 100,000 | 35 | 35 |
| Total | 100,000 | 45 | 33 | 100,000 | 61 | 39 | 100,000 | 35 | 35 |

To sum up, implementing a least-cost prioritization process reduces water-quality preservation even if the conservation area is greater (65 versus 35 hectares for a €100,000 budget) since the VBWs selected are less effective.

Based on a mean per-hectare cost, Table 2 confirms this result since unconnected VBWs are the cheapest whereas they are the least effective for water-quality preservation.^{xiii} Furthermore, a cost-effective prioritization process based on mean per-hectare costs would lead to VBWs connected upstream being selected ahead of VBWs connected downstream because €3,173/ha is less than €3,512/ha and VBWs connected upstream are more effective than those connected downstream in the qualitative classification presented before. However, a surprising a priori result is that the mean per-hectare costs are ranked in opposing ways for both the Armançon and Brenne watersheds when considered separately. To understand this counterintuitive result, Table 1 is helpful. On the one hand, Table 1 shows that the €3,512/ha mean is mainly driven by the VBWs connected downstream in the Brenne watershed, which are more widespread and expensive on a mean per-hectare basis than in the Armançon watershed. On the other hand, Table 1 shows that the €3,173/ha mean is mainly driven by the VBWs connected upstream in the Armançon watershed which are more widespread and less expensive on a mean per-hectare basis than in the Brenne watershed. A policy implication is that the mean per-hectare cost should be considered with caution because it can hide local disparities. This implication is particularly relevant for agencies operating over widespread jurisdictions. The need for caution surrounding the mean per-hectare cost criteria is also true within watersheds where the distribution of per-hectare costs can differ from the mean (see Figure App-2 to App-3 that confirm this

^{xiii} The criteria are in competition for the entire distribution of the per-hectare costs, and not only the mean. Indeed, Figure App-1 shows that the Lorenz curve for unconnected VBWs is invariably above the curve for connected VBWs. Consequently, focusing on a mean price is a good approximation for connected and unconnected VBWs in the Brenne and Armançon watersheds.

difference for VBWs connected upstream versus downstream and with high versus low permeability). This result confirms that the prioritization procedure must be conducted as in Tables 3 and 4: ranking VBWs from the cheapest to the most expensive, by effective types and beginning with the most effective type.

6. Conclusion and extensions

To the best of our knowledge, our work is the first to provide an integrated framework of valley-bottom wetland conservation for surface water-quality preservation in agricultural landscapes. This integrated framework consists of combining perspectives from both soil science and economics for the selection of VBWs to be conserved first for water-quality preservation purposes when there is no reliable method for quantifying water-quality benefits. Our analysis stresses the importance of the simultaneous consideration of hydrogeomorphic and cost criteria when prioritizing VBWs for conservation. Indeed, concentrating on either one or the other can reduce the impact on water-quality preservation within the framework of a constrained budget.

A good candidate for conservation is a VBW that has the best possible retention function from a hydrogeomorphic perspective as well as the lowest cost from an economic perspective. We identify situations in which these criteria are compatible (when the lowest-cost VBWs are the ones with the best retention function) and other situations in which they are competitive (when the lowest-cost VBWs are the ones with the poorest retention function, for instance). The policy implications are direct. In a case in which the criteria are compatible, the qualitative method of VBW classification for water-quality preservation is adapted to prioritize VBWs, whereas in a case in which the criteria are competing, the prioritization must also consider the cost of conservation. An integrated cost-effective criterion must then be implemented.

Furthermore, our local prediction of VBWs allows us to consider upstream VBWs in the analysis. National predictions are usually not accurate enough to precisely identify upstream VBWs, and tend to focus on downstream VBWs. Our analysis highlights that upstream VBWs can be of great importance for water-quality preservation. This contribution is particularly relevant in a context of climate change. Indeed, since rainfall variability will increase in the future (see, for instance, GIECC, 2013), downstream VBWs will flood more often, which will reduce their retention function.

This work could be extended in several ways. First, we adopt a lower-bound estimation of the costs, since we ignore any post-purchase costs, such as those linked to the maintenance of the land after it is put out of production. An extension could consist of collecting and integrating such costs. It would

then be interesting to work on degraded VBWs (potential minus existing one from the PEEW approach). However, this is beyond the scope of the present paper.

The conservation method that we consider in this work can be viewed as an extreme method because it includes purchasing land for conservation purposes. A more flexible method could focus on restricting land use. Such restrictions could control the agricultural use of land, banning drainage, for instance. Such restrictions also have a cost, and can either decrease or increase the nutrient-retention function. Investigating the cost and the impact on the retention function of each restriction of land use could be a second extension of this work. It would then be useful to determine the best combination of purchases and agricultural land-use restrictions for conserving the nutrient-retention function of VBWs.

Yang *et al.* (2016) propose a hydrologic modeling approach to quantify the efficiency of riparian wetlands in terms of nutrient retention. A third extension of our work would be to apply our integrated analysis to hydrology in order to quantify the nutrient-retention capacity of VBWs. Once this retention capacity has been quantified, it would then be possible to perform a complete cost-efficiency analysis by computing the economic value of nutrient retention as Byström (1998) or Grossman (2012) do for other types of wetlands. However, such an exercise, would need to be conducted with caution because of the imprecision of methods for estimating the existence value of natural goods such as water (Kelman, 1981; Spash and Aslaksen, 2015).

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Appendices

Appendix 1: Variables used in the econometric models

Table App-1: Description of variables used in the models

| Variables | Variable complete name | Units |
|--------------------------------------|--|---------------------|
| Location characteristics of the plot | | |
| DistMun_less2 | Distance to Municipality less than 2 kilometers | kilometers |
| DistMun_more2 | Distance to Municipality more than 2 kilometers | kilometers |
| TDistRetPlace_less10 | Travel Distance to Retail Place less than 10 kilometers | kilometers |
| TDistRetPlace_10-20 | Travel Distance to Retail Place between 10 and 20 kilometers | kilometers |
| TDistRetPlace_more20 | Travel Distance to Retail Place more than 20 kilometers | kilometers |
| RetPlace_dijon | Retail Place Dijon | 1: yes - 0: no |
| Armançon_manag | Armançon water management scheme | Share of area |
| Arroux_manag | Arroux water management scheme | Share of area |
| Ouche_manag | Ouche water management scheme | Share of area |
| Tille_manag | Tille water management scheme | Share of area |
| Vouge_manag | Vouge water management scheme | Share of area |
| Topographic characteristics | | |
| Ln_surf_less5 | Surface area less than 5,000 square meters | 1,000 square meters |
| Ln_surf_5-15 | Surface area between 5 and 15 square meters | 1,000 square meters |
| Ln_surf_15-30 | Surface area between 15 and 30 square meters | 1,000 square meters |
| Ln_surf_more_30 | Surface area more than 5,000 square meters | 1,000 square meters |
| Altitude_less200 | Altitude less than 200 meters | meters |
| Altitude_more200 | Altitude more than 200 meters | meters |
| Slope | Slope | degrees |
| Soil properties | | |
| Texture_vf | Texture very fine | 1: yes - 0: no |
| Texture_f | Texture fine | 1: yes - 0: no |
| Texture_m | Texture medium | 1: yes - 0: no |
| Texture_c | Texture coarse | 1: yes - 0: no |
| Control variables | | |
| Brenne | Brenne watershed | Share of area |
| Armançon | Armançon watershed | Share of area |
| Year_1992 | Transaction in 1992 | 1: yes - 0: no |
| Year_1993 | Transaction in 1993 | 1: yes - 0: no |
| Year_1994 | Transaction in 1994 | 1: yes - 0: no |

| | | |
|-------------|---------------------|------------------------------|
| Year_1995 | Transaction in 1995 | 1: yes - 0: no |
| Year_1996 | Transaction in 1996 | 1: yes - 0: no |
| Year_1997 | Transaction in 1997 | 1: yes - 0: no |
| Year_1998 | Transaction in 1998 | 1: yes - 0: no |
| Year_1999 | Transaction in 1999 | 1: yes - 0: no |
| Year_2000 | Transaction in 2000 | 1: yes - 0: no |
| Year_2001 | Transaction in 2001 | 1: yes - 0: no |
| Year_2002 | Transaction in 2002 | 1: yes - 0: no |
| Year_2003 | Transaction in 2003 | 1: yes - 0: no |
| Year_2004 | Transaction in 2004 | 1: yes - 0: no |
| Year_2005 | Transaction in 2005 | 1: yes - 0: no |
| Year_2006 | Transaction in 2006 | 1: yes - 0: no |
| Year_2007 | Transaction in 2007 | 1: yes - 0: no |
| Year_2008 | Transaction in 2008 | 1: yes - 0: no |
| FarmerPurch | Farmer Purchaser | 1: yes - 0: no |
| Field | Field | 1: cultivated land 0: meadow |

Table App-2: Descriptive statistics of variables used for estimations (N=6,477)

| Continuous variables | Mean | Standard Deviation | Minimum | Maximum |
|-----------------------------|-------------|---------------------------|----------------|----------------|
| Surface area | 21 | 39 | 0.02 | 841 |
| Altitude | 309 | 111 | 176 | 689 |
| Slope | 3 | 3 | 0.0003 | 25 |
| DistMun | 1.36 | 0.89 | 0.03 | 5.84 |
| TDistRetPlace | 11 | 6 | 0 | 36 |
| Armançon_manag | 0.163 | 0.369 | 0 | 1 |
| Arroux_manag | 0.106 | 0.308 | 0 | 1 |
| Ouche_manag | 0.097 | 0.294 | 0 | 1 |
| Tille_manag | 0.094 | 0.292 | 0 | 1 |
| Vouge_manag | 0.067 | 0.249 | 0 | 1 |
| Brenne | 0.094 | 0.292 | 0 | 1 |
| Armançon | 0.043 | 0.202 | 0 | 1 |
| Dummy variables | | | | |
| Texture_vf | 0.260 | 0.439 | 0 | 1 |
| Texture_f | 0.501 | 0.500 | 0 | 1 |
| Texture_m | 0.194 | 0.395 | 0 | 1 |
| Texture_c | 0.045 | 0.207 | 0 | 1 |
| Year_1992 | 0.063 | 0.244 | 0 | 1 |
| Year_1993 | 0.069 | 0.253 | 0 | 1 |
| Year_1994 | 0.052 | 0.222 | 0 | 1 |
| Year_1995 | 0.050 | 0.217 | 0 | 1 |
| Year_1996 | 0.051 | 0.219 | 0 | 1 |
| Year_1997 | 0.041 | 0.197 | 0 | 1 |
| Year_1998 | 0.057 | 0.232 | 0 | 1 |
| Year_1999 | 0.049 | 0.215 | 0 | 1 |
| Year_2000 | 0.052 | 0.222 | 0 | 1 |
| Year_2001 | 0.054 | 0.227 | 0 | 1 |
| Year_2002 | 0.050 | 0.218 | 0 | 1 |
| Year_2003 | 0.055 | 0.227 | 0 | 1 |
| Year_2004 | 0.062 | 0.242 | 0 | 1 |
| Year_2005 | 0.064 | 0.245 | 0 | 1 |
| Year_2006 | 0.067 | 0.249 | 0 | 1 |
| Year_2007 | 0.078 | 0.269 | 0 | 1 |
| Year_2008 | 0.086 | 0.281 | 0 | 1 |
| Field | 0.709 | 0.454 | 0 | 1 |
| FarmerPurch | 0.274 | 0.446 | 0 | 1 |
| RetPlace_dijon | 0.080 | 0.272 | 0 | 1 |

Table App-3: Descriptive statistics of variables used for predictions (N=42,189)

| Continuous variables | Mean | Standard Deviation | Minimum | Maximum |
|-----------------------------|-------------|---------------------------|----------------|----------------|
| Surface area | 20 | 38 | 0.02 | 716 |
| Altitude | 380 | 82 | 199 | 596 |
| Slope | 4 | 3 | 0.0003 | 25 |
| DistMun | 1.41 | 0.86 | 0.01 | 5.30 |
| TDistRetPlace | 15 | 8 | 0 | 36 |
| Armançon_manag | 0.766 | 0.421 | 0 | 1 |
| Arroux_manag | 0.001 | 0.023 | 0 | 0.981 |
| Ouche_manag | 0.002 | 0.043 | 0 | 1 |
| Tille_manag | 0.009 | 0.096 | 0 | 1 |
| Vouge_manag | 0 | 0 | 0 | 0 |
| Brenne | 0.495 | 0.500 | 0 | 1 |
| Armançon | 0.282 | 0.450 | 0 | 1 |
| Dummy variables | | | | |
| Texture_vf | 0.185 | 0.388 | 0 | 1 |
| Texture_f | 0.807 | 0.395 | 0 | 1 |
| Texture_m | 0.008 | 0.091 | 0 | 1 |
| Texture_c | 0 | 0 | 0 | 1 |
| Year_1992 | 0 | 0 | 0 | 0 |
| Year_1993 | 0 | 0 | 0 | 0 |
| Year_1994 | 0 | 0 | 0 | 0 |
| Year_1995 | 0 | 0 | 0 | 0 |
| Year_1996 | 0 | 0 | 0 | 0 |
| Year_1997 | 0 | 0 | 0 | 0 |
| Year_1998 | 0 | 0 | 0 | 0 |
| Year_1999 | 0 | 0 | 0 | 0 |
| Year_2000 | 0 | 0 | 0 | 0 |
| Year_2001 | 0 | 0 | 0 | 0 |
| Year_2002 | 0 | 0 | 0 | 0 |
| Year_2003 | 0 | 0 | 0 | 0 |
| Year_2004 | 0 | 0 | 0 | 0 |
| Year_2005 | 1 | 0 | 1 | 1 |
| Year_2006 | 0 | 0 | 0 | 0 |
| Year_2007 | 0 | 0 | 0 | 0 |
| Year_2008 | 0 | 0 | 0 | 0 |
| Field | 0.509 | 0.500 | 0 | 1 |
| FarmerPurch | 0 | 0 | 0 | 0 |
| RetPlace_dijon | 0.006 | 0.078 | 0 | 1 |

Appendix 2: Hedonic price function estimations

Table App-4: OLS results (coefficients and standard errors) for our model

| Variables | Estimated coefficients | Robust standard errors |
|-------------------------------------|------------------------|------------------------|
| Ln_surf_less5 | +0.479*** | 0.030 |
| Ln_surf_5-15 | +0.672*** | 0.018 |
| Ln_surf_15-30 | +0.766*** | 0.014 |
| Ln_surf_more_30 | +0.842*** | 0.010 |
| Altitude_less200 | -0.003*** | 0.000 |
| Altitude_more200 | -0.001*** | 0.000 |
| Slope | -0.023*** | 0.006 |
| DistMun_less2 | -0.294*** | 0.028 |
| DistMun_more2 | -0.168*** | 0.017 |
| TDistRetPlace_less10 | -0.040*** | 0.012 |
| TDistRetPlace_10-20 | -0.024*** | 0.005 |
| TDistRetPlace_more20 | -0.012*** | 0.003 |
| RetPlace_dijon | +1.311*** | 0.204 |
| RetPlace_dijon_TDistRetPlace_less10 | -0.065* | 0.034 |
| RetPlace_dijon_TDistRetPlace_10-20 | -0.062*** | 0.014 |
| RetPlace_dijon_TDistRetPlace_more20 | -0.049*** | 0.010 |
| Armançon_manag | -0.224*** | 0.084 |
| Arroux_manag | -0.157*** | 0.048 |
| Ouche_manag | +0.005 | 0.074 |
| Tille_manag | +0.258*** | 0.067 |
| Vouge_manag | +0.329*** | 0.085 |
| Texture_vf | -0.194*** | 0.043 |
| Texture f | Ref. | Ref. |
| Texture_m | -0.220*** | 0.034 |
| Texture_c | -0.219** | 0.094 |
| Year_1992 | -0.666*** | 0.065 |
| Year_1993 | -0.671*** | 0.058 |
| Year_1994 | -0.698*** | 0.061 |
| Year_1995 | -0.588*** | 0.060 |
| Year_1996 | -0.522*** | 0.058 |
| Year_1997 | -0.602*** | 0.064 |
| Year_1998 | -0.428*** | 0.067 |
| Year_1999 | -0.332*** | 0.065 |
| Year_2000 | -0.237*** | 0.071 |
| Year_2001 | -0.367*** | 0.070 |
| Year_2002 | -0.107 | 0.067 |
| Year_2003 | -0.102* | 0.059 |
| Year_2004 | -0.128** | 0.059 |
| Year_2005 | Ref. | Ref. |
| Year_2006 | +0.186** | 0.080 |
| Year_2007 | +0.129** | 0.064 |
| Year_2008 | +0.154** | 0.062 |
| Field | +0.106*** | 0.028 |
| FarmerPurch | -0.273*** | 0.025 |
| Brenne | +0.019 | 0.085 |
| Armancon | -0.055 | 0.094 |
| Intercept | 7.563*** | 0.100 |

| Variables | Estimated coefficients | Robust standard errors |
|------------------------|------------------------|------------------------|
| Number of observations | 6,477 | |
| R ² | 0.7187 | |

*Significant at 10% level, **Significant at 5% level, ***Significant at 1% level

Table App-5: OLS results (coefficients and standard errors) for Hilal *et al.* (2016) model

| Variables | Estimated parameters | Robust standard errors |
|-----------------------|----------------------|------------------------|
| Ln_Surface_less5 | +0.480*** | 0.031 |
| Ln_Surface_5-15 | +0.666*** | 0.020 |
| Ln_Surface_15-30 | +0.761*** | 0.015 |
| Ln_Surface_more30 | +0.836*** | 0.011 |
| Altitude_less200 | -0.003*** | 0.000 |
| Altitude_more200 | -0.002*** | 0.000 |
| Slope | -0.029*** | 0.006 |
| DistMun_less2 | -0.287*** | 0.030 |
| DistMun_more2 | -0.161*** | 0.020 |
| TDistRetPlace_less10 | -0.043*** | 0.013 |
| TDistRetPlace_10-20 | -0.030*** | 0.006 |
| TDistRetPlace_more20 | -0.020*** | 0.004 |
| TDistUrb_add_less15 | -0.029*** | 0.006 |
| TDistUrb_add_more15 | -0.010*** | 0.002 |
| TDistDijon_add_less15 | -0.029*** | 0.005 |
| TDistDijon_add_more15 | -0.008*** | 0.001 |
| Texture_vf | -0.465*** | 0.108 |
| Texture_vf_f | -0.216*** | 0.060 |
| Texture_vf_m | -0.369*** | 0.072 |
| Texture f | Ref. | Ref. |
| Texture_f_vf | -0.099** | 0.050 |
| Texture_f_m | -0.146** | 0.062 |
| Texture_m | -0.204*** | 0.058 |
| Texture_m_c | -0.338*** | 0.078 |
| Texture_m_f | -0.221*** | 0.064 |
| Texture_c | -0.282** | 0.111 |
| Texture_c_o | -0.312 | 0.223 |
| Year_1992 | -0.617*** | 0.066 |
| Year_1993 | -0.650*** | 0.057 |
| Year_1994 | -0.670*** | 0.060 |
| Year_1995 | -0.577*** | 0.061 |
| Year_1996 | -0.493*** | 0.057 |
| Year_1997 | -0.601*** | 0.065 |
| Year_1998 | -0.411*** | 0.067 |
| Year_1999 | -0.303*** | 0.065 |
| Year_2000 | -0.213*** | 0.070 |
| Year_2001 | -0.316*** | 0.062 |
| Year_2002 | -0.113* | 0.068 |
| Year_2003 | -0.116* | 0.060 |
| Year_2004 | -0.090 | 0.059 |
| Year_2005 | Ref. | Ref. |
| Year_2006 | +0.192** | 0.077 |

| | | |
|------------------------|-----------|-------|
| Year_2007 | +0.148** | 0.066 |
| Year_2008 | +0.139** | 0.063 |
| Field | +0.134*** | 0.029 |
| FarmerPurch | -0.273*** | 0.025 |
| Intercept | +8.263*** | 0.142 |
| Number of observations | 6,477 | |
| R ² | 0.7115 | |

*Significant at 10% level, **Significant at 5% level, ***Significant at 1% level

Appendix 3: Local threshold values of topographic wetness indices

Table App-6: Threshold values of IBK_{ls} and IBK_{hs} according to Strahler order, permeability of parent material, and geology

| Strahler order | Permeability of parent material | Number of transects | Geology | Threshold values | |
|----------------|---------------------------------|---------------------|-----------------------------|-------------------|-------------------|
| | | | | IBK _{ls} | IBK _{hs} |
| 1 to 3 | Low | 3 | Marl and clay from Armançon | 11 | - |
| | | 2 | Marl and clay from Brenne | 14 | - |
| | | 2 | Granite | 15 | - |
| | | 2 | Alluvium | 13 | - |
| | High | 1 | Limestone | 11 | - |
| | | 1 | Sandy marl | 11 | - |
| | | 2 | Alluvium | 16,5 | - |
| 4 and more | Low | 1 | Marl and clay | - | 13 |
| | | 2 | Granite | - | 12,4 |
| | | 2 | Alluvium | - | 14,5 |
| | High | 2 | Alluvium | - | 17 |

Appendix 4: Sensitivity analysis of the least-cost prioritization process to the available budget

Table App-7: VBW selected in the least-cost prioritization process with a budget of €500,000

| | Armançon | | | Brenne | | | Both | | |
|----------------------|----------------|-----------|------------|----------------|------------|------------|----------------|-----------|------------|
| | Cost (€) | Number | Area (ha) | Cost (€) | Number | Area (ha) | Cost (€) | Number | Area |
| Unconnected | 408,355 | 66 | 226 | 405,711 | 82 | 214 | 418,077 | 72 | 244 |
| Connected downstream | 40,281 | 6 | 21 | 36,229 | 13 | 18 | 21,977 | 5 | 12 |
| Upstream impermeable | 50,190 | 7 | 27 | 58,060 | 21 | 29 | 58,773 | 15 | 32 |
| Upstream permeable | 1,173 | 1 | 1 | - | - | - | 1,173 | 1 | 1 |
| Total | 500,000 | 80 | 275 | 500,000 | 116 | 261 | 500,000 | 93 | 289 |

Table App-8: VBW selected in the least-cost prioritization process with a budget of €1,000,000

| | Armançon | | | Brenne | | | Both | | |
|----------------------|------------------|------------|------------|------------------|------------|------------|------------------|------------|------------|
| | Cost (€) | Number | Area (ha) | Cost (€) | Number | Area (ha) | Cost (€) | Number | Area |
| Unconnected | 664,284 | 116 | 352 | 612,311 | 124 | 302 | 716,996 | 127 | 397 |
| Connected downstream | 144,336 | 20 | 73 | 284,925 | 40 | 122 | 126,357 | 18 | 65 |
| Upstream impermeable | 190,206 | 26 | 96 | 102,765 | 30 | 49 | 155,474 | 25 | 81 |
| Upstream permeable | 1,173 | 1 | 1 | - | - | - | 1,173 | 1 | 1 |
| Total | 1,000,000 | 163 | 522 | 1,000,000 | 194 | 472 | 1,000,000 | 171 | 543 |

Table App-9: VBW selected in the least-cost prioritization process with a budget of €5,000,000

| | Armançon | | | Brenne | | | Both | | |
|----------------------|------------------|------------|--------------|------------------|------------|--------------|------------------|------------|--------------|
| | Cost (€) | Number | Area (ha) | Cost (€) | Number | Area (ha) | Cost (€) | Number | Area |
| Unconnected | 296,2822 | 491 | 1,306 | 205,0362 | 411 | 780 | 308,7881 | 529 | 1422 |
| Connected downstream | 394,817 | 51 | 181 | 1,974,457 | 271 | 658 | 657,771 | 93 | 295 |
| Upstream impermeable | 1,627,586 | 213 | 684 | 958,738 | 180 | 314 | 1,238,638 | 180 | 545 |
| Upstream permeable | 14,775 | 5 | 6 | 16,443 | 9 | 5 | 15,711 | 6 | 7 |
| Total | 5,000,000 | 760 | 2,177 | 5,000,000 | 871 | 1,757 | 5,000,000 | 808 | 2,268 |

Table App-10: VBW selected in the least-cost prioritization process with a budget of €10,000,000

| | Armançon | | | Brenne | | | Both | | |
|----------------------|-----------|--------|-----------|-----------|--------|-----------|-----------|--------|-------|
| | Cost (€) | Number | Area (ha) | Cost (€) | Number | Area (ha) | Cost (€) | Number | Area |
| Unconnected | 5,672,092 | 936 | 2,221 | 3,250,157 | 836 | 1,044 | 5,788,978 | 1,002 | 2,400 |
| Connected downstream | 661,028 | 83 | 270 | 4,312,916 | 767 | 1,148 | 1,204,301 | 182 | 494 |
| Upstream impermeable | 3,591,867 | 483 | 1,351 | 2,161,484 | 534 | 567 | 2,958,925 | 428 | 1,174 |
| Upstream permeable | 75,013 | 21 | 27 | 44,561 | 41 | 11 | 47,796 | 17 | 18 |

| | Armançon | | | Brenne | | | Both | | |
|-------|------------|--------|-----------|-----------|--------|-----------|------------|--------|-------|
| | Cost (€) | Number | Area (ha) | Cost (€) | Number | Area (ha) | Cost (€) | Number | Area |
| Total | 10,000,000 | 1,523 | 3,869 | 9,769,117 | 2,178 | 2,770 | 10,000,000 | 1,629 | 4,087 |

Appendix 5: Sensitivity analysis of the cost-effective prioritization process to the amount of budget available

Table App-11: VBW selected in the cost-effective prioritization process with a budget of €500,000

| | Armançon | | | Brenne | | | Both | | |
|----------------------|----------------|------------|------------|----------------|------------|------------|----------------|------------|------------|
| | Cost (€) | Number | Area (ha) | Cost (€) | Number | Area (ha) | Cost (€) | Number | Area |
| Unconnected | - | - | - | - | - | - | - | - | - |
| Connected downstream | - | - | - | - | - | - | - | - | - |
| Upstream impermeable | 399,877 | 60 | 192 | 455,439 | 104 | 172 | 355,317 | 61 | 175 |
| Upstream permeable | 100,123 | 45 | 33 | 44,561 | 41 | 11 | 144,683 | 86 | 44 |
| Total | 500,000 | 105 | 225 | 500,000 | 145 | 183 | 500,000 | 147 | 219 |

Table App-12: VBW selected in the cost-effective prioritization process with a budget of €1,000,000

| | Armançon | | | Brenne | | | Both | | |
|----------------------|------------------|------------|------------|------------------|------------|------------|------------------|------------|------------|
| | Cost (€) | Number | Area (ha) | Cost (€) | Number | Area (ha) | Cost (€) | Number | Area |
| Unconnected | - | - | - | - | - | - | - | - | - |
| Connected downstream | - | - | - | - | - | - | - | - | - |
| Upstream impermeable | 899,877 | 119 | 402 | 955,439 | 180 | 314 | 855,317 | 138 | 390 |
| Upstream permeable | 100,123 | 45 | 33 | 44,561 | 41 | 11 | 144,683 | 86 | 44 |
| Total | 1,000,000 | 164 | 434 | 1,000,000 | 221 | 324 | 1,000,000 | 224 | 434 |

Table App-13: VBW selected in the cost-effective prioritization process with a budget of €5,000,000

| | Armançon | | | Brenne | | | Both | | |
|----------------------|------------------|------------|--------------|------------------|------------|--------------|------------------|------------|--------------|
| | Cost (€) | Number | Area (ha) | Cost (€) | Number | Area (ha) | Cost (€) | Number | Area |
| Unconnected | - | - | - | - | - | - | - | - | - |
| Connected downstream | - | - | - | 2793955 | 373 | 862 | - | - | - |
| Upstream impermeable | 4,899,877 | 632 | 1,723 | 2,161,484 | 534 | 567 | 4,855,317 | 682 | 1,762 |
| Upstream permeable | 100,123 | 45 | 33 | 44,561 | 41 | 11 | 144,683 | 86 | 44 |
| Total | 5,000,000 | 677 | 1,756 | 5,000,000 | 948 | 1,439 | 5,000,000 | 768 | 1,806 |

Table App-14: VBW selected in the cost-effective prioritization process with a budget of €10,000,000

| | Armançon | | | Brenne | | | Both | | |
|----------------------|-----------|--------|-----------|-----------|--------|-----------|-----------|--------|-------|
| | Cost (€) | Number | Area (ha) | Cost (€) | Number | Area (ha) | Cost (€) | Number | Area |
| Unconnected | 3,517,332 | 601 | 1,510 | 3,250,157 | 836 | 1,044 | - | - | - |
| Connected downstream | 806,357 | 116 | 310 | 4,312,916 | 767 | 1,148 | 2,117,644 | 276 | 782 |
| Upstream impermeable | 5,576,189 | 958 | 1,874 | 2,161,484 | 534 | 567 | 7,737,673 | 1,492 | 2,441 |
| Upstream permeable | 100,123 | 45 | 33 | 44,561 | 41 | 11 | 144,683 | 86 | 44 |

| | Armançon | | | Brenne | | | Both | | |
|-------|------------|--------|-----------|-----------|--------|-----------|------------|--------|-------|
| | Cost (€) | Number | Area (ha) | Cost (€) | Number | Area (ha) | Cost (€) | Number | Area |
| Total | 10,000,000 | 1,720 | 3,726 | 9,769,117 | 2,178 | 2,770 | 10,000,000 | 1,854 | 3,267 |

Appendix 6: Lorenz curves of the per-hectare costs of VBWs

The Lorenz curve is a cumulative frequency curve that compares the distribution of a variable with the uniform distribution. The diagonal orientation of the graph depicts the uniform distribution. The more the Lorenz curve lies below the diagonal, the more unevenly the price is shared between various VBWs.

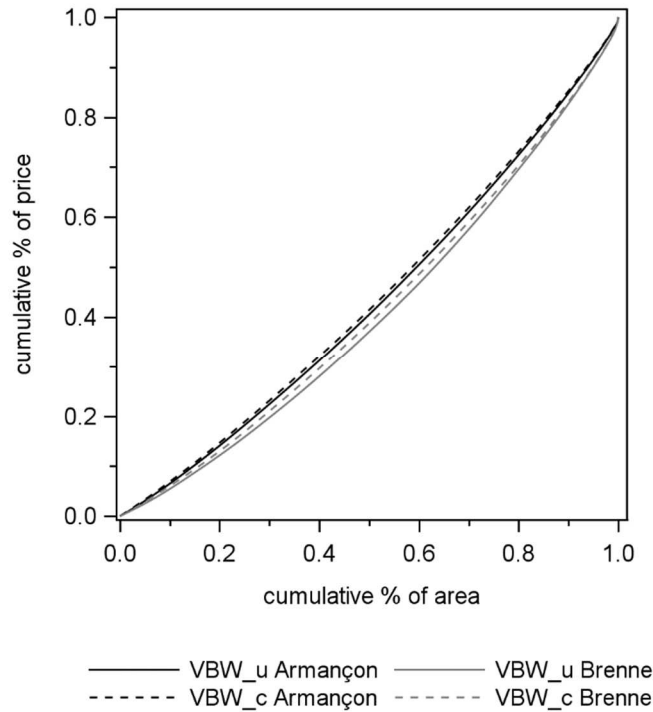


Figure App-1: Distribution of the per-hectare costs in the Brenne and Armançon watersheds for connected versus unconnected VBWs

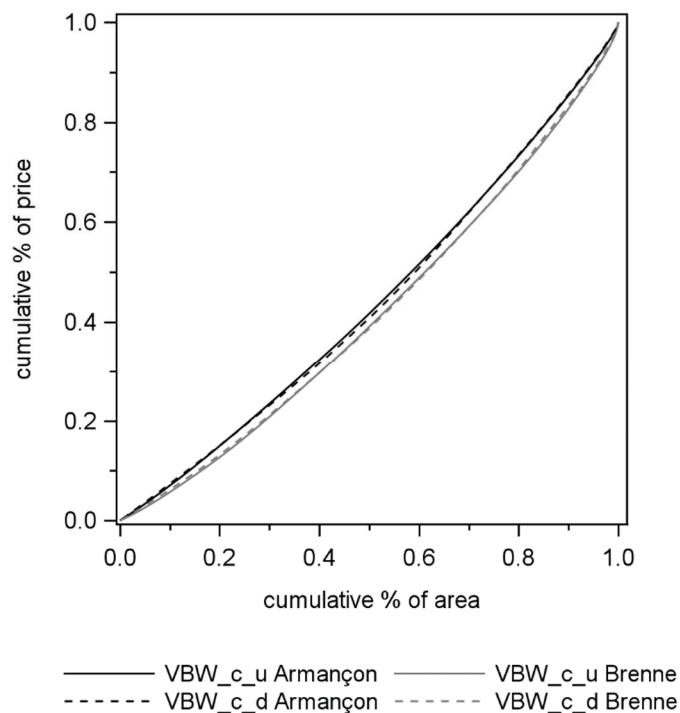


Figure App-2: Distribution of the per-hectare costs in the Brenne and Armançon watersheds for upstream connected versus downstream connected VBWs

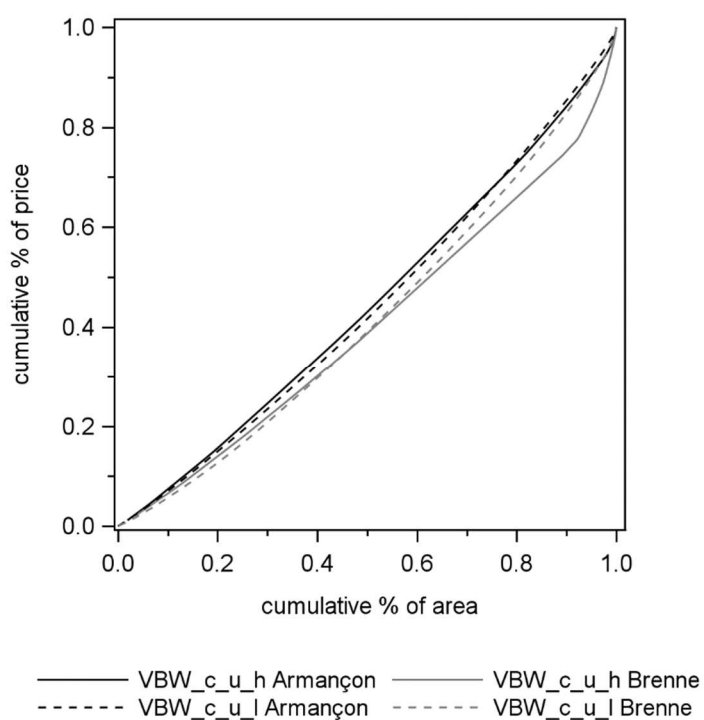


Figure App-3: Distribution of the per-hectare costs in the Brenne and Armançon watersheds for upstream connected VBWs on high permeability parent material versus upstream connected VBWs on low permeability parent material