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Guides and protocols

Guide on setting up buffer zones

to limit the transfer of farm contaminants

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This guide was drafted by the "*Integrating buffer zones in river-basin management to prevent farm nonpoint-source pollution*" technical group, called **the Buffer-zone technical group**.

The mission of the Buffer-zone technical group (BZTG) is to lead and promote the study of buffer zones in order to prevent farm nonpoint-source pollution by bringing together an array of experts and skills (scientific, operational, decision-making, etc.) in a wide range of disciplines (agronomy, environmental science, human and social sciences, etc.).

The technical group, led by Onema* and Irstea, includes members from the Agriculture and Ecology ministries, research organisations, local State services, agricultural representatives, river-basin managers and project leaders, drinking-water managers, environmental-protection groups, the Union of plant-protection industries, consulting firms, etc.

Its structure makes the BZTG a particularly useful meeting place for researchers and river-basin managers who are confronted on a daily basis with the difficulties involved in setting up realistic and effective action plans. These contacts confront different points of view (scientific and operational) and contribute to guiding the development of tools and methods prior to their use in the field over the short and mid term.

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* As of 1 January 2017, the Agency for marine protected areas, the Technical workshop for natural areas, the National agency for water and aquatic environments (Onema) and the French national parks joined forces to form the **French biodiversity agency**.

Guide on setting up buffer zones
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Abstract

This guide sums up the currently available knowledge on setting up buffer zones to limit the transfer of farm substances (pesticides, nutrients) to aquatic environments.

The first chapter provides information on transfer processes and presents the various steps in assessing the situation in order to propose effective scenarios in rural areas.

The second chapter presents in detail the various solutions to control the transfer of contaminants using buffer zones, discusses their creation depending on the selected approach and provides information on their effectiveness.

Numerous references to the existing literature are also provided for further study of each step, ranging from the preliminary studies to the actual design and creation of buffer zones.

Keywords

Buffer zone, transfer process, pesticides, nitrates, phosphorous, suspended solids, assessment, effectiveness, sizing

Contents

Introduction

Since the 1980s, interest in buffer zones, i.e. spaces between or along fields intended to limit the transfer of farm contaminants to aquatic environments, has grown considerably in step with constant improvements in the technical information available on the subject. **In parallel with good farming practices, buffer zones are highly effective in controlling and limiting the transfer of farm contaminants to aquatic environments.** They can also fulfil other functions, e.g. regulate water flows and attenuate flood risks, combat erosion of farm land, preserve biodiversity and landscapes, etc., which make them truly useful tools for territorial development in river basins.

What topics does this guide address?

This guide is the result of work done by the Buffer-zone technical group managed jointly by Onema and Irstea [➔]. It presents information and data to assist in decision-making concerning buffer zones intended to preserve surface and groundwater from nonpoint-source pollution from farms. It follows in the steps of the guide published by Corpen[1] in 2007, *The environmental functions of buffer zones, the scientific and technical basis for water protection*, but includes new information concerning the functioning and effectiveness of the different buffer systems, notably water bodies that were not addressed in the Corpen document.

➔ *http://zonestampons.onema.fr/*

Who should read this guide?

This document is intended primarily for technical personnel involved in setting up buffer zones. To make the most of this document, the reader must possess a wide range of engineering knowledge in territorial planning, hydrology, rural hydraulics, pedology, agronomy, hydrochemistry, etc.

This document may also serve as reference material for project managers, territorial coordinators, river technicians or farming-advice service personnel in:

- better understanding the range of potential solutions for control over transfer of farm contaminants using buffer zones, taking into account the conditions specific to their territory;
- drafting technical specifications;
- preparing technical presentations for project meetings.

What role can this guide play in setting up a buffer zone?

The creation of buffer zones and, more generally, development work in river basins to protect water resources must go through a number of steps in identifying the best solutions for a given project objective. The steps are summarised below in Table 1.

As noted in the table, this guide may be used during the second step to prepare recommendations on creating effective buffer zones to meet the specific constraints of each project, where the first step consists of identifying and understanding those constraints. In this sense, it is similar to the guide published by Irstea in 2010 *[Gril* et al.*, 2010]* that presented a decision tree to assist in selecting, among the potential

1. Corpen: Guidelines committee for environmentally friendly agricultural practices

solutions, the system best suited to controlling the transfer of plant-protection products. However, this guide goes further in that it expands the recommendations to other types of substances and processes.

This is because buffer zones are capable of providing several functions in preserving water and aquatic environments:

- control over erosion, flows of suspended solids and contaminants adsorbed by the suspended solids;
- control over flows of water containing dissolved contaminants, e.g. pesticides and nutrients (dissolved nitrates and phosphorous);
- limiting the drift of sprayed chemical products.

To achieve these results, the buffer zone must above all be capable of intercepting the above flows. The buffer zone should be positioned in the path of the water, between the source fields and the receiving aquatic environment. For this reason, they are suited above all for the interception of surface transfers (diffuse runoff or concentrated flows) and for sub-surface transfers (sub-surface flows and drainage water). The objective of the buffer zone is to slow the water flows and increase the contact time between the contaminants, the soil and the vegetation in order to strengthen the natural retention and degradation processes (physical-chemical and/or biological).

However, it should be noted that, depending on their position on the slope and the relevant context, not all buffer zones are capable of meeting the same objectives. It is indispensable to gain in-depth knowledge on the processes involved (and on the constraints weighing on project feasibility) in order to select the best system in accordance with the set objective. To that end, the approach presented in this guide consists of analysing the local situation (identifying the transfer processes) in view of proposing a set of suitable solutions deemed to be effective on the basis of the currently available technical information.

Table 1. The steps in creating buffer zones to protect aquatic environments from nonpoint-source pollution

	Necessary questions	Required knowledge	Tools	Expected results
Clarify the situation	■ Characterise the contamination: type of contaminant, concentration, frequency of threshold overruns, etc.? ■ Origin of the contamination, periods when it occurs, type(s) of transfer?	■ Use of agricultural products (periods, zones where used, dosages). ■ Transfer of contaminants to the natural environment, starting from its use in the field to its transfer toward and to the receiving aquatic environment.	■ Analysis of environmental contamination (monitoring of water quality). ■ Analysis of vulnerabilities and pressures exerted in the territory.	■ Identify and understand the processes involved in the contamination of the aquatic environment. ■ Set objectives for the action plan, decide on the resources invested and prioritise zones for work.
Identify and advise solutions	■ What are the potential corrective measures: agronomic solutions and/or buffer zones? ■ If a buffer zone is adopted, what type of buffer system is the best suited and the most acceptable (cost, amount of land required, etc.)? ■ What are the territorial constraints & benefits of the best site?	■ Functioning of buffer zones and conditions governing their effectiveness, depending on the set objective.	■ In-depth analysis of transfers and paths of water on the concerned slope and in the vulnerable fields. ■ Analysis of existing buffer zones, of malfunctions and deficiencies in protection. ■ **Operational analysis for selecting and positioning buffer zones to ensure effective protection of water resources.**	■ Propose development scenarios for a level of effectiveness accepted by the various stakeholders in the territory.
Implement the solutions	■ What are the design rules (sizing, vegetation, etc.)? ■ How should management and maintenance be organised? ■ What are the applicable regulations?	■ Ecological engineering, civil engineering, hydraulics and rural hydrology. ■ Planting techniques, mowing/trimming techniques, etc. ■ Legislation and administrative formalities, territorial issues.	■ Quantification of flows (water and contaminants) on the slope intercepted by the buffer zone. ■ Sizing tools and charts. ■ Guide or technical specifications for the design process and for maintenance.	■ Creation of an effective buffer zone meeting the set objectives.

How should this guide be used?

It is necessary to be fully familiar with the transfer processes of farm contaminants to aquatic environments *[see Section 1.2., p. 16]* and one must of course have correctly analysed the site to identify the potential solutions *[see Section 1.3., p. 24]*. These prerequisites are reviewed briefly in the first chapter of this document and discussed in greater detail as needed in the operational analysis (the second chapter), in terms of how buffer zones function.

The operational analysis *[see Chapter 2, p. 31]* begins by selecting the type of contaminant, then determining the type of transfer and/or the hydraulic concentration of the flows *[see Table 3, p. 31]*. The distinctions between these various categories are due essentially to the forms of action, specific to each type of buffer system, against the substances polluting aquatic environments. For each analysed situation, a set of recommendations is made concerning the selection and positioning of suitable buffer zones, with information on buffer sizing and, in some cases, on buffer effectiveness. Further details are provided in the Annexes *[see p. 47]*.

This guide is above all a decision-aid tool to assist in pointing the reader to more detailed literature informing on the design and sizing criteria specific to each type of buffer system.

Note to readers

The recommendations presented in this document are general guidelines that should be systematically reviewed to ensure that they apply to the specific, local situation.

The use of buffer zones in rural areas to control the transfer of farm contaminants is not necessarily a sufficient solution under all agricultural/pedological/climatic conditions and does not avoid the need to adopt good practices in the fields themselves. In most cases, the two solutions are complementary and the buffer zones serve above all to manage the risks raised by any residual transfers.

Agronomic techniques used in the fields are not discussed in this document, however they must be taken into account at each step in the processes presented here in order to take advantage of all possibilities to limit nonpoint-source pollution.

1 ■ Prerequisites for operational analysis

The first section [2] of Chapter 1 provides information intended to establish a common vocabulary (names, definitions, descriptions) for the various types of buffer systems. The second section of this chapter reviews the main transfer processes of farm contaminants to the receiving aquatic environments. Finally, the chapter ends with a discussion of the preliminary studies on which the subsequent recommendations will be based. Particular attention will be paid to the coordination between studies carried out on different scales, to study procedures and to the elements that must imperatively be covered by the studies in order to proceed with the operational analysis in the second chapter.

1.1 ■ The different types of buffer system

The term buffer zone is used here to designate any area between or along fields in rural settings, intended to intercept and to attenuate (retain and/or degrade) the transfer of farm contaminants to aquatic environments. In general, buffer zones are simple solutions, designed to be easy to set up at a low cost, and require minimal maintenance. In this sense, they implement ecological-engineering techniques in that they attempt to make use of and optimise contaminant retention and degradation processes found in natural environments.

Given their purifying function, buffer zones may be seen as semi-curative systems (compared to preventive solutions based on agronomic techniques implemented on site in the fields), but that does not avoid the need to adopt good practices in the fields themselves. In most cases, the two solutions are complementary and the buffer zones serve above all to manage the risks raised by any residual transfers specific to certain agricultural/pedological/climatic conditions.

The term buffer zone may thus designate different types of elements in the landscape:

- some elements, such as wet meadows, wooded areas, ponds, upland reservoirs, etc., already existed or were initially put into place for a particular function, e.g. irrigation, and their role as a buffer zone is a secondary feature;
- others, such as grass buffer strips, fascines (bundled wood) and constructed wetlands, are purposely positioned, developed, managed and maintained to ensure their role as buffers and to optimise their effects on a given type of substance and/or on a given type of transfer.

Buffer zones may be divided according to a number of characteristics, e.g. type of vegetation, dimensions, hydric status, etc., with some buffer systems combining several characteristics or representing intermediate cases. In this document, five main categories will be presented:

- grass buffer strips;
- ligneous systems;
- embankments and bunds;
- ditches;
- water bodies.

2. The information presented here is in large part a reproduction of the information available on the site http://zonestampons.onema.fr/ *and in the guide published by Corpen in 2007. It is highly advised to read the latter guide for more detailed information.*

This typology, though useful in as much as it is descriptive, does not mean that buffer systems in a given category necessarily offer the same functions. The design and implementation conditions must always be analysed before deciding which type of buffer system is best suited to a given objective.

1.1.1 Grass-based systems

Grass buffer strips include all buffer zones where the vegetation, whether spontaneous or planted, is made up of herbaceous plants (primarily grasses). These are probably the simplest buffer systems (easy to set up and to maintain) and the least expensive, but they are not suitable for all types of situations (types of contaminant and the corresponding transfer process) and may need to be very large to achieve a satisfactory level of effectiveness.

Grass buffer strips consist above all of the grass buffer zones made legally mandatory along watercourses by various regulations, e.g. Good agro-environmental conditions (GAEC), the Nitrates directive, the regulation on pesticide-free zones (ZNT) *[Fig. 1]*. They also serve to intercept runoff from slopes at the interface between fields, near ditches, around sinkholes. They are essentially strips of land of variable width, generally covered by herbaceous vegetation that has often been intentionally planted (primarily grasses such as ryegrass or fescue). Other types of cover (leguminous plants, flowers mixed with grasses) may also be useful in stimulating biodiversity (pollinating organisms, beneficial organisms, etc.).


Irstea

Fig. 1. Mandatory buffer strip along a watercourse.


Areas

Fig. 2. Headland at the bottom of a field.

Planting grass in strategically positioned headlands at the ends of fields *[Fig. 2]* is also a solution, though the repeated passage of the farm equipment risks damaging the zone and limiting its effectiveness. If that is the case, the headland must be widened.

Field corners with grass. This is a derived form of grass buffer strips, generally found in fields with a double slope converging to a corner that must be correctly managed *[Fig. 3]*.


Irstea

Fig. 3. Field corner with grass, extending the mandatory buffer strip.

Irstea

Fig. 4. Talweg with grass.

Vegetated (grass) talwegs. In this case, the talweg (generally with no permanent flow) between two opposing slopes comprises herbaceous plants to slow the flows arriving from the slopes and limit the risk of concentrated flows and the resulting erosion *[Fig. 4]*.

Tracks in fields often concentrate runoff water and it may be useful to plant them in order to slow and limit flows *[Fig. 5]*.

Irstea

Fig. 5. Tracks and inter-row spaces with grass in a vineyard.

The narrow edges of fields generally run along ditches or roads *[Fig. 6]*. Contrary to grass strips, these edges are often narrow (less than one metre wide) and colonised by spontaneous vegetation.

Irstea

Fig. 6. Narrow field edge between the field and a road.

Pastures are natural or planted areas, that may be permanent or temporary, and are often intended for grazing or hay production *[Fig. 7]*. In the bottom of a valley, certain areas, called bottomland pastures or wet meadows, tend to be saturated with water a large part of the year and are generally of low agronomic value.

Irstea

Fig. 7. Bottomland pasture with a wooded hedgerow and planted trees.

Idle land is abandoned farm land that is no longer maintained. It is rapidly colonised by spontaneous vegetation and will tend naturally to become woodland. This type of land may be very useful as a buffer zone.

1.1.2 Ligneous systems

The term "ligneous systems" designates buffer systems where the vegetation consists essentially of shrubs and trees. This particular characteristic enables these systems to provide more functions than grass-based systems, thus making them more suitable in certain cases. On the other hand, they require more maintenance than grass-based systems and when they are created from scratch, they require several years before becoming fully effective.

Riparian vegetation consists of areas of variable width, comprising specific types of plant species, lining the banks of rivers *[Fig. 8]*. The vegetation consists of storeys of trees, shrubs and herbaceous plants that are generally well suited to large quantities of water at a relatively low depth (willows, poplars, birch, alder, etc.). Riparian vegetation provides a wide range of environmental functions such as river-bank maintenance, flood control, mitigation of aquatic pollution and, in general, preservation of the ecological quality of watercourses (thermal regulation, shelter for aquatic and terrestrial fauna, etc.).


Irstea

Fig. 8. Riparian vegetation lining the banks of a stream.

Hedgerows on flat land or embankments consist of planted vegetation, shrubs and/or trees, forming lines across the landscape and, in some cases, entire networks (in bocage landscapes) between and around fields *[Fig. 9]*. It is known that they regulate the transfer of water within catchments and are important factors in maintaining biodiversity (ecological networks).


Irstea

Fig. 9. Damaged bocage landscape in a mixed-crop and livestock farming area.

Dense hedges are designed (suckering species) and worked on to produce very dense stands of stalks ("hydraulic combs") *[Fig. 10]*, which are very effective in terms of limiting erosion.


Areas

Fig. 10. Hedge with very dense stalks.

Fig. 11. Copse standing a the corner of a field.

Groves and copses are stands of trees covering highly variable surface areas, ranging from a few square metres to several hectares *[Fig. 11]*. They are frequently found in areas where excess water builds up (wet patches, bottomlands, alluvial forests), in which case they are comparable to riparian vegetation. When located higher up on slopes, they may provide the same functions as hedgerows in terms of water transfer and erosion.

Fig. 12. A fascine with new wood added.

Fascines (bundled wood). This type of ligneous system is in a category of its own and is used most often to combat erosion *[Fig. 12]*. Fascines are man-made and consist of bundles of branches or thin trunks placed between stakes. The wood used (generally willow) may be "dead", in which case it must be regularly renewed, or "living", in which case it can take root and eventually develop into a hedgerow.

1.1.3 Embankments and bunds

Embankments and bunds are small levees of soil running along a field. They generally range in height from 0.5 to 1.5 metres *[Fig. 13]*. Whether consisting of grass or hedges, they have a significant impact on the paths taken by water in rural areas by locally blocking surface flows, directing water in a particular direction or temporarily retaining it.

Fig. 13. Example of a bund planted with a hedge running along a talweg.

1.1.4 Ditches

Ditches typically represent an intermediate type of buffer zone in that they share a number of characteristics with grass-based systems and with water bodies. Traditionally, ditches in rural areas are installed for hydraulic reasons, i.e. to evacuate water to limit erosion and improve fields (drainage systems), and to collect water from roads. They are thus an integral part of upriver, hydrographic networks and, due to their position so far upriver, they constitute one of the main interfaces between farmed fields and surface aquatic environments. They are of major importance in collecting and conveying farm contaminants, and for this reason, they are often seen as negative factors in that they enable the rapid transfer of contaminated water to the receiving aquatic environments. As interstitial spaces that already exist in rural landscapes, ditches nonetheless represent an opportunity in that, with suitable design and management, they could serve to retain and purify water, particularly if they are vegetated [3].

Vegetated ditches contain permanent vegetation that is sufficiently dense (high roughness) that it can slow flows and increase the residence time of water and contaminants in the ditch *[Fig. 14]*.

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Fig. 14. A vegetated ditch between two cultivated fields.

Ditches with check dams are a type of ditch that can slow flows and act as a buffer. They are divided by low "dams" that create a series of compartments *[Fig. 15]* with the water flowing from one to the next, but in which part of the water can stagnate and infiltrate the soil.

Irstea

Fig. 15. A ditch with check dams.

3. Care must be taken with ditches because according to certain local by-laws, they may be considered a watercourse and subject to the corresponding management rules.

1.1.5 Water bodies

This type of system includes all open-air water bodies, whether man-made or not, intended to intercept and temporarily store all or part of flows of water and contaminants arriving from agricultural fields located at a higher elevation. They are particularly well suited for the management of hydraulically concentrated flows, whether runoff via existing systems (ditches) or flows caused by agricultural drainage.

Irstea

Fig. 16. Pond.

Pools and ponds vary widely in size but do not exceed 5 000 square metres and a depth of two metres. They may be permanent or temporary *[Fig. 16]*. The shallow depth enables sunlight to penetrate and plants to take root on the bottom (at least along the banks). They are often found in wetlands that have been modified by humans and may be equipped with specific hydraulic management systems to regulate the water level (primarily the case for ponds). They are generally supplied by runoff water, but they may also be located in areas where the water table rises to just below the surface.

Irstea

Fig. 17. A typical upland reservoir.

Upland reservoirs are man-made reservoirs in low spots in hilly terrain. They are blocked off by one or more dikes (or dams) *[Fig. 17]* and are supplied by runoff water or by a permanent or non-permanent watercourse (definition drafted by the Rhône-Méditerranée-Corse Water agency). The water may be stored for a number of uses, the most frequent being irrigation and attenuation of low-flow levels during the summer.

Irstea

Fig. 18. A constructed wetland buffer zone.

Constructed wetland buffer zones (CWBZ) are rustic installations just downstream of a collection network for concentrated flows (ditches, agricultural drainage) designed specifically to temporarily store water and further its purification before it is returned to the receiving aquatic environment *[Fig. 18]*. The presence of stagnant water encourages the rapid installation of wetland-specific plant species.

Lhyges

Fig. 19. Storm basin with natural vegetation in Rouffach.

Existing installations in the hydrosystem may also be put to greater use. An example is the small basins set up to protect against floods (storm basins) *[Fig. 19]*. Even though they are artificial (concrete structures, stone banking, etc.), any modifications that increase the residence time of small runoff volumes (vegetation, gravel filter, regulation of discharges) would enhance their purification capabilities.

1.2 ■ Transfer processes of farm contaminants to aquatic environments

With the exception of handling incidents and accidental releases of certain products, pollution of aquatic environments by farm substances is generally of the nonpoint-source type, i.e. it comes from a number of sources spread over time and space. Even when these substances are used in compliance with regulations, the size of the surface areas involved means that, in sensitive environments, residual concentrations may be found in aquatic environments that exceed quality standards for drinking water and/or that negatively impact the environment (eutrophication, ecotoxicological risks, etc.). This type of contamination is also likely to persist in the environment for a more or less long period, an example being Atrazine and its metabolites, a substance prohibited in 2004, but that is still detected in aquatic environments. The difficulties created by this type of pollution for the protection of water resources become clear if we consider that it is necessary to take action over the mid to long term in a coordinated manner over entire regions.

In as much as they are positioned as interfaces between the sources of pollution and aquatic environments, buffer zones represent a potential solution to meet the problems caused by nonpoint-source contamination. **They must, of course, be set up in parallel with agronomic solutions to reduce and better manage inputs in the fields.**

1.2.1 The different types of hydric transfer

The main substances used by farms and causing pollution in aquatic environments are nutrients (nitrogen and phosphorus via fertiliser) and plant-protection products for crops (herbicides, fungicides, insecticides and molluscicides). Each of these substances produces different effects in the environment and, starting from the field where they are applied, can be transported in different manners to the receiving aquatic environments (surface or groundwater). The types of transfer are listed below.

➔ **Transfer via runoff**, when water and the contaminants flow on the surface of the ground and rapidly reach surface aquatic environments, either directly or via a network of collection ditches. In this case, an important distinction must be made between two different processes for which buffer zones will not produce the same results:

- ***Horton overland flow***, when rainfall has exceeded soil infiltration capacity;
- ***saturation excess overland flow***, when rain falls on soil that is already saturated with water and cannot infiltrate.

Similarly, a distinction must be made between:

- ***diffuse runoff***, when the water is fairly evenly spread across the ground surface and flows in a sheet wash or in unstable rivulets;
- ***concentrated runoff***, when, due to the local topographical characteristics (talweg) or even to micro-topographical features (ruts left by machines, plough lines, etc.), the flows converge and shift to a preferred path, gather speed and turbulence that can result in erosion (incision).

➔ **Sub-surface transfers**, also called hypodermic flows, when water and contaminants circulate laterally at a slight depth below the soil surface or form a sub-surface sheet of water (notably in basement formations). In this case, the water can meet the surface if there is a sudden break in the slope (the foot of an embankment or a river bank).

➔ Transfers via sub-surface drainage systems, when water and contaminants that have infiltrated the soil meet drainage systems installed under fields that often receive excess water (hydromorphic soil). In this case, the water is rapidly returned to the hydrographic network via ditches or directly to the nearest watercourse.

➔ Transfers due to deep infiltration, when water and contaminants travel vertically through the soil and the non-saturated zone, and flow into the groundwater. Deep infiltration may occur:

- ***in a diffuse and relatively slow manner*** when infiltration takes place via the soil matrix (inter-granular pores);
- ***in a concentrated and rapid manner*** (without transiting the soil) when a surface flow reaches an infiltration "spot" (frequent in karstic environments).

➔ In addition to these hydric transfers, there is also **the drift of sprayed products** through the air that occurs when various substances are applied to crops (mainly plant-protection products [4]). A part of the products misses the targeted crops and settles on land outside the field when the droplets are transported on the wind. Some of the drifting products may directly reach a water body [5].

The occurrence and intensity of the various types of transfer mentioned above depend on the properties of the environment (soil, lithology, topography, climate, etc.), but also on the farming installations and practices which can amplify or mitigate certain processes. The analysis of a given area in terms of these factors (assessment phase *[see Section 1.3.]*) should reveal the various, potential transfer processes and their spatial distribution in view of adopting the most suitable protection measures for the water resources.

Among the environmental factors, particular attention must be paid to the role played by the soil depending on its hydric properties. For example, it is important to characterise or to identify:

- soil permeability and/or its sensitivity to capping which can lead to non-infiltration and to more or less significant runoff depending on the intensity of the rainfall (Horton overland flow);
- indications of hydromorphy signalling soil that has been saturated with water over a long period and favourable conditions for runoff (runoff over saturated soil);
- soil porosity and thickness, two factors determining the potential for water storage (usable water reserves) prior to the transition to lateral or vertical flows;
- differing degrees of permeability between the various soil horizons (including a plowpan) or at the interface between the soil and the substratum, likely to cause lateral flows at shallow depths (sub-surface flows) and saturation excess overland flow.

The climate also affects the intensity of the various transfers over the seasons:

- depending on the intensity of rainfall, a more or less favourable factor in generating Horton overland flow;
- depending on the hydric balance (a function of rainfall and evapotranspiration), i.e. the quantity of water that will effectively supply groundwater reserves and watercourses, with a risk of more or less significant transfers depending on the season and the current usable water reserves.

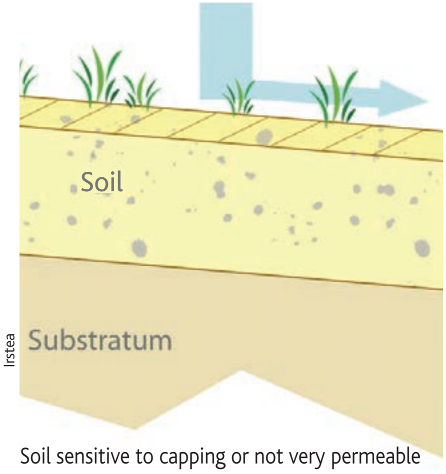
Finally, the topography also plays a role, in terms of the slope (which can increase erosion), the position of the field in the catchment (bottomlands are clearly more likely to be saturated with water), and generally speaking it will determine how surface flows take place (with a progressive concentration of flows from upstream to downstream).

4. Another phenomenon is the volatilisation/fallout of ammonium nitrogen during the spreading of organic fertiliser.

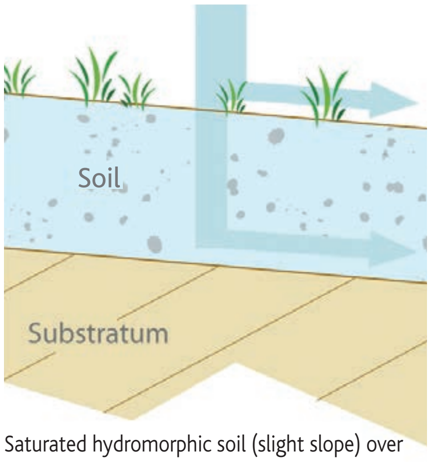
5. This type of transfer will not be discussed here. The means of limiting the risks of spray drift using buffer zones is based on two factors:

- *the creation of a pesticide-free zone in order to avoid applying products in the immediate vicinity of water bodies (see the applicable regulations);*
- *a "barrier" effect designed to intercept the droplets carried by the wind.*

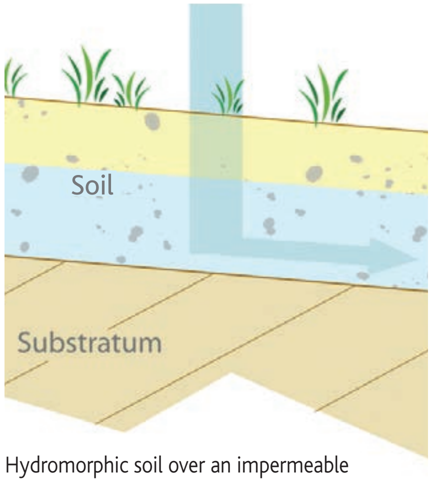
All these interacting factors explain the diversity of transfer situations in a given area *[Fig. 20]* **that must be carefully analysed during the assessment** *[see Section 1.3.]*.



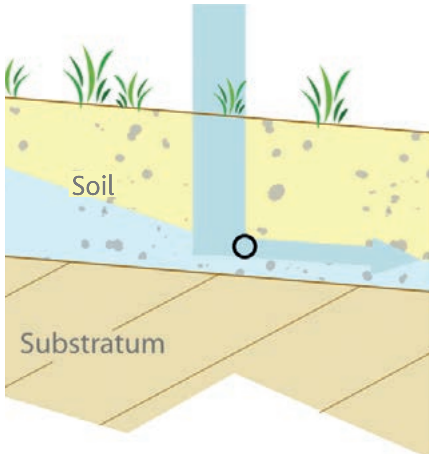
Soil sensitive to capping or not very permeable on the surface
➔ Primarily Horton overland flow



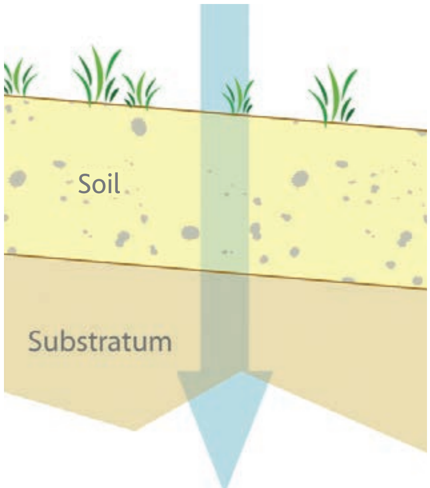
Saturated hydromorphic soil (slight slope) over an impermeable substratum
➔ Primarily runoff over saturated soil or hypodermic flows



Hydromorphic soil over an impermeable substratum
➔ Primarily hypodermic flows



Drained hydromorphic soil over an impermeable substratum
➔ Primarily agricultural drainage



Permeable soil and substratum
➔ Infiltration to groundwater

Fig. 20. Illustration of a few typical transfer processes depending on the environmental properties. The substrata shown here may designate the bedrock (alluvial, carbonated, crystalline formations) or the overlaying layers resulting from mineral alteration (decalcification clays in carbonated environments, sites of basement alteration), which may or may not be aquiferous sites.

Above and beyond the environmental characteristics, the agricultural practices and methods employed in a given field can also reinforce or mitigate certain types of transfer by modifying the soil surface. Of particular note are:

- buried drain pipes intended to improve certain types of soil subject to excess water. Drains limit the risks of runoff over saturated soil. On the other hand, soil water is removed rapidly and in a concentrated manner to the ditches or even directly to the hydrographic network (however the transfer is not as fast as runoff due to the buffer effect of the soil);
- the methods used to prepare the soil, for example ploughing which can increase, on a more or less temporary basis, the permeability, roughness and porosity of the soil and thus limit rapid transfer by runoff. This is notably the case in areas subject to soil capping, where hoeing once the crops have emerged

is a means to recreate surface roughness and enhance infiltration [6]. But soil that has been compacted by farm vehicles (notably during harvesting) can inhibit infiltration and increase runoff in fields;

• soil cover provided by plants or crop residues (mulch) at different stages in crop rotations. The stalks, leaves and other debris can slow surface runoff by increasing the roughness and thus encourage infiltration in the soil.

Agronomic solutions exist on the field level, notably in terms of the agricultural processes selected (i.e. the type of crop and technique) to limit (or promote) certain types of transport. Generally speaking, it should be noted that the organisation and management of farm land (layout and size of fields, diversity of crop systems, rotations and processes) play an important role in transfers on the catchment level. A diversified territory (a "patchwork of crops") is generally preferable from the point of view of the diversity of soil surfaces and the resulting transfer risks, as well as in terms of the agricultural substances that are spread over different time spans and areas. These issues are not discussed here, but should be taken into consideration in order to use every possible technique in controlling the transfer of agricultural contaminants to aquatic environments.

Given the great diversity in agricultural/pedological/climatic conditions and in the corresponding transfer modes, the behaviour of agricultural substances can vary depending on how they are applied and on their physical-chemical properties and notably their greater or lesser solubility or, to the contrary, their capacity to bond with soil particles (i.e. fixing to clay and organic matter). Whereas the most soluble substances are easily transported by water, whatever the type of transport, the fate of adsorbed substances depends considerably on the transport of soil particles (suspended solids *[see Section 1.2.6.]*).

The following sections present in detail the specific aspects for each type of substance in order to better understand how buffer zones can be used to control their transfer to aquatic environments.

1.2.2 Nitrate transfers

The nitrate ion (NO_3^-) is one of the mineral forms of nitrogen. It is the most easily available and usable by plants. Nitrates are part of a complex cycle comprising chemical and biological reactions in the various compartments of the soil, biosphere, hydrosphere and the atmosphere *[Fig. 21, next page]*. They are highly soluble and not readily retained by the compounds existing in the soil, which explains why they are easily transported by water and constitute one of the main causes of pollution in surface and groundwater. With phosphorous, nitrates are the cause of eutrophication and at high doses, they can be toxic for animal life.

The nitrate ion is naturally present in soil and water in concentrations close to 10 mg/l *[Meybeck, 1982]*). However, it may exist in excess and cause pollution if an imbalance occurs between fertiliser inputs and the decomposition of organic matter (mineralisation of the organic nitrogen), on the one hand, and that which is effectively consumed by the crops, on the other.

6. Work on the soil can also produce undesirable effects by creating conditions conducive to erosion (e.g. a storm following hoeing) or by creating a plowpan that limits deep water infiltration and hinders good root development of the crops. Ploughing can also "dilute" the organic matter that is a positive factor for biological activity, and reduce the retention of certain contaminants and the structural stability of the soil.

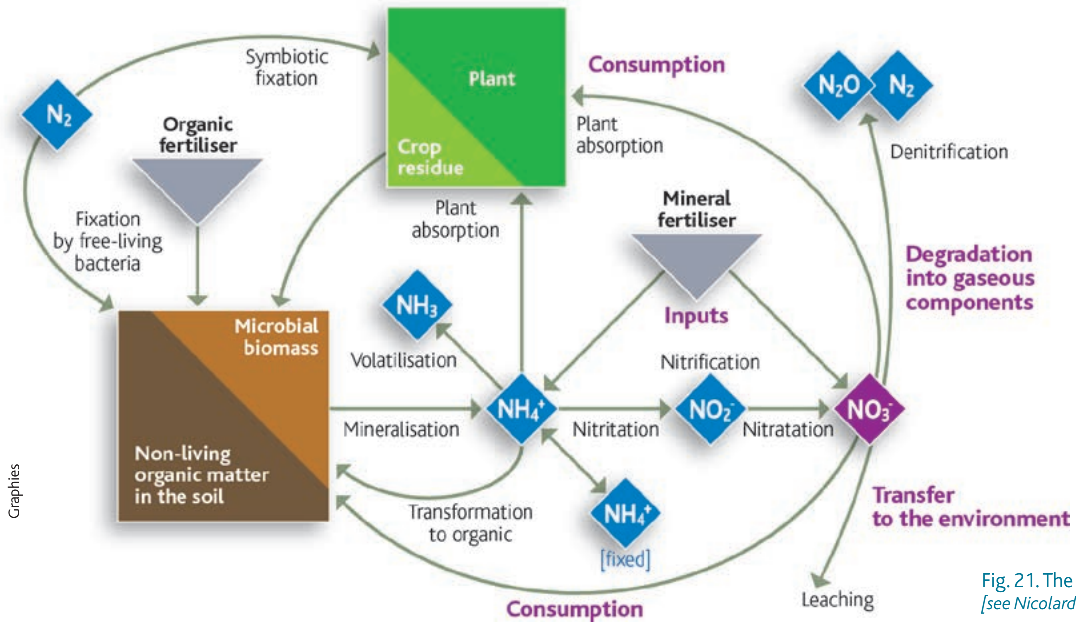


Fig. 21. The nitrogen cycle
[see Nicolardot et al.*, 1996]*.

Given their characteristics, nitrate ions are transported to the receiving aquatic environments by three main transfer mechanisms, 1) sub-surface flows in the soil, 2) buried drainage pipes and 3) deep infiltration to groundwater. Transfers occur generally during periods with high hydric levels (mainly in the winter), when the maximum level of usable water reserves is reached and consumption by the vegetation is low. The excess water circulates vertically or laterally in the soil and carries the nitrate ions with it to the groundwater or to watercourses (leaching). On the other hand, runoff water would appear to be a negligible factor in nitrate transfers, but may be more effective for other forms of nitrogen *[see Section 1.2.3.]*.

With the exception of absorption by roots and assimilation by the microbial biomass, which results in only temporary storage of the nitrogen (which is returned to the environment over the short to mid term [7], unless the vegetation is removed), denitrification is the only way to degrade the nitrate ion in the environment. This process takes place essentially under anoxic conditions in saturated environments (water bodies, saturated soil) where certain bacteria naturally present in the environment transform the nitrate ions into gaseous by-products (N_2O and N_2) in order to extract the oxygen they need [8].

The phenomenon is more or less effective depending on the presence of assimilable carbon (organic matter), the temperature conditions and the pH. On the other hand, when denitrification is incomplete (partial anoxia), this process can produce nitrous oxide (N_2O), a gas that contributes strongly to the greenhouse effect. Consequently, limiting the amounts of nitrogen inputs in fields (and using intermediate crops to trap the nitrates) is the best means to avoid the negative effects caused by excess nitrate levels in the environment.

1.2.3 Transfer of organic nitrogen and ammonium ions

When they are spread as organic fertilisers (primarily liquid and dry manure [9]) or as ammonium fertilisers (capable of fixing to organic matter), nitrogen inputs are not always incorporated into the soil where they can mineralise and become available for crops. If they remain partially on the surface, the inputs can be transported by runoff water and reach surface aquatic environments where they contribute to increasing nitrate levels (after mineralisation and oxidation).

7. This return process is more or less progressive (depending on the mineralisation of the organic matter), i.e. nitrate absorption can regulate the flows to some extent and limit peak concentrations.

8. It should be noted that denitrification can, on a more marginal level, take place in deeper groundwater, when the rock constituting the aquifer contains a certain level of iron sulfides (pyrite). In this case, the mechanism involves an oxidation reaction that releases iron, sulfates and dinitrogen (this reaction is called autotrophic denitrification).

9. This includes grazed pastures where transfer risks also exist for animal waste. It should be noted that organic fertiliser derived from animals may also represent a source of bacterial contamination.

1.2.4 Phosphorous transfers

Similar to nitrogen, phosphorous is an indispensable nutrient for the growth of crops. It is assimilated by plants in the form of a phosphate ion dissolved in the water in soil. Generally however, it is present in particulate form adsorbed by the various soil compounds, with a particular capacity for bonding with iron, aluminium, calcium and organic matter. Though phosphorous is not particularly toxic for living beings, its excess is one of the main causes of eutrophication in surface aquatic environments. There are many sources of phosphorous released to the environment, including nonpoint sources (mineral and organic fertilisers) and point sources such as effluents from wastewater-treatment plants and potentially defective sewer networks that collect water loaded with household and industrial detergents.

Assimilation of phosphorous by crops is generally limited because its availability is reduced by its high capacity to bond with soil particles. Contrary to nitrogen, phosphorous does not undergo a transformation process that would make possible exchanges with the atmosphere (i.e. there is no gaseous form). Phosphorous tends to accumulate over more or less long periods in the soil, depending on the physical-chemical conditions (redox, pH, etc.).

Mobilisation phenomena may occur (particularly under redox conditions when shallow groundwater rises closer to the surface [10]), with a part of the phosphorous present in the soil being dissolved (approximately 5 to 10%, rarely more), however, most of the phosphorous input to aquatic environments is in particulate form via erosive runoff (when the soil particles are drawn off and transported by the water). In this case, the fate of the phosphorous is directly linked to that of the suspended solids *[see Section 1.2.6.]*.

1.2.5 Transfer of plant-protection products

On farms, plant-protection products comprise a group of substances (insecticides, herbicides, fungicides and molluscicides) intended primarily to combat crop pests (bioaggressors, undesired plants). They can be applied in different manners (spray targeting the soil or leaves, treatments on seeds or plants, etc.), using different doses and at specific times, all depending on the desired effect. In health and environmental terms, these products can be highly toxic for animal life, notably because of bioaccumulation of toxins as they move up the food chain and because of product mixtures that are poorly understood to date.

Contamination of aquatic environments by plant-protection products involves a large number of relatively complex factors. This is due to the great diversity of substances, of their properties and of the many physical-chemical and biological mechanisms involved, that further depend on the agricultural/pedological/climatic conditions governing their behaviour in the environment. It is important to note that during a treatment and depending on the local conditions (wind, humidity, etc.), a variable proportion of the product does not produce its full effect, either because it does not reach the target [11] or because its effect is delayed or only partial. This residual quantity of the product will be subjected to the various processes (retention, degradation or dispersal) in the environment *[Fig. 22, next page]*.

If no rain falls following the treatment and depending on the substance applied, one part may drift off (volatilisation) or be photodegraded, two phenomena that progressively reduce the quantity of the residual substance. When it does rain, the treated surfaces (leaves, soil) are leached and the products are transported by the water on the soil surface and through the soil. It is clear that the time between the treatment and the first significant rain is one of the most important factors in determining the transfer risks of plant-protection products (in terms of the quantities available for transfer).

10. This may in particular be the case given the reduction of the iron oxides to which the phosphorous bonds. Note the opposition in the conditions favourable for denitrification and those for retaining adsorbed phosphorous.

11. Atmospheric drift may transport the applied products outside the field and even directly into a water body.

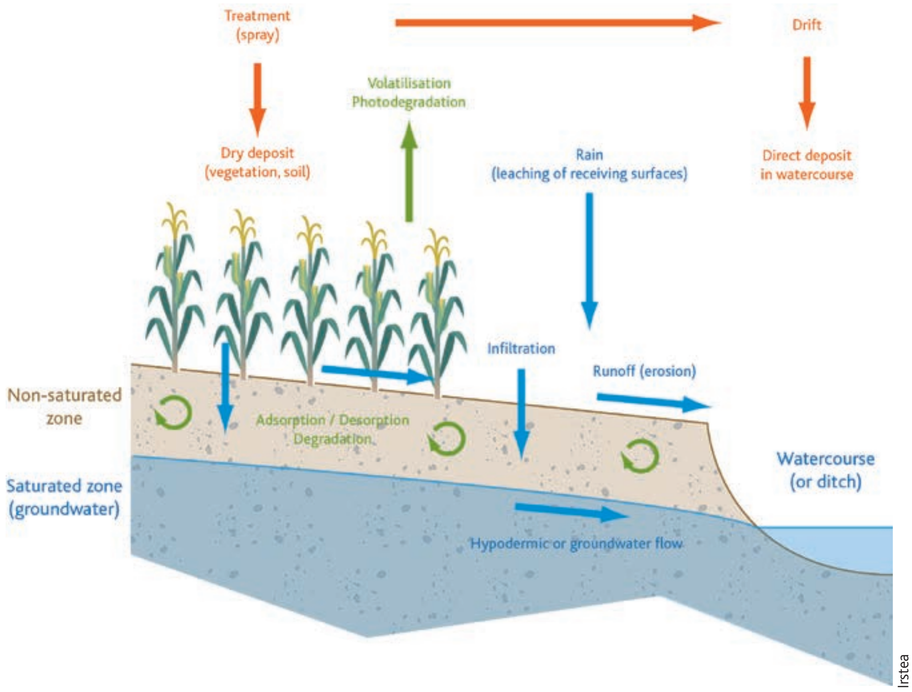


Fig. 22. Pesticide retention, dissipation and dispersal processes in the environment.

From that point on, the fate of the substance (retention, degradation or transfer to the aquatic environment) depends on two fundamental properties explained below, having to do with its mobility and its persistence in the environment, factors that directly influenced by the soil characteristics [12].

• ***The mobility*** of a substance depends on its capacity to bond with the soil solids and notably the potential for ion exchange. Mobility is estimated using the soil organic carbon-water partitioning coefficient (Koc). This parameter determines the proportion between the dissolved plant-protection products and those retained by the soil particles. Retention is all the more effective that the soil contains organic matter and fine particles, and the Koc coefficient is high. If that is not the case, a high percentage of the substance remains dissolved and will be easily carried off by the water. The percentage of retention is not necessarily stable. The mechanisms governing adsorption may work in reverse (desorption) and depend on complex physical-chemical balances that can change over time. This explains in part why certain molecules may be observed in an environment a long time after having been applied.

• ***Persistence*** is often expressed as the DT50 dissipation time of a molecule, i.e. the time required for 50% of the applied substance to be dissipated. This time can vary from a few days to several months, depending on the molecule. Whether calculated in the lab or in the field, the DT50 indicates the speed at which each molecule degrades in the environment. This depends primarily on the biological activity of the soil, which itself depends on the soil humidity, temperature and the quantity of organic matter. A rapidly degraded molecule will generally be transported in lesser quantities to the receiving aquatic environments (if it encounters favourable conditions for its degradation). It should be noted, however, that degradation often leads to the formation of by-products (called metabolites) that may also be toxic (though generally less than the original molecule) and may persist for more or less long times in the environment, depending on their specific sensitivity to the processes of retention, degradation and dispersal. Finally, the potential for degradation is also determined by the availability of the substance, i.e. part of the adsorbed substance cannot be degraded by the micro-organisms in the soil. For all the above reasons, it is clearly the processes of retention and degradation that determine the potential quantities of transferred plant-protection products.

12. The information presented here provides the means to understand the main mechanisms at work, however it has been greatly simplified. For more in-depth information, see the collective science-advice study titled "Fate and transfer of pesticides in the environment and the biological impacts", Aubertot J.N., J.M. Barbier, A. Carpentier, J.J. Gril, L. Guichard, P. Lucas, S. Savary, I. Savini, M. Voltz (editors), 2005. Pesticides, agriculture and the environment. Reducing the use of pesticides and limiting their environmental impact. Collective science-advice study, INRA and Cemagref, Chapter 3.

On the basis of the above, four major observations may be made concerning the transfer of plant-protection products to aquatic environments.

• ***The proportion of pesticide that can be transferred*** from a field to aquatic environments generally represents a very small percentage of the applied quantity (often less than 2% and rarely more than 10%), but that is often sufficient to cause significant contamination of water resources.

• ***The dissolved fraction*** (higher for molecules with a low Koc) is likely to be transported by water, whatever the transfer mode, whereas the adsorbed fraction (higher for molecules with a high Koc) will depend on the fate of the suspended solids *[see Section 1.2.6.]*.

• ***The level of organic matter in soil*** is probably one of the most decisive factors in the capability of soil to act as en effective filter for plant-protection products, in terms of both retention and the biological activity required for their degradation. The surface horizon is often the richest when it has not been disturbed by tillage. The potential for dissipation drops with the depth and is virtually inexistent by the time the products reach the groundwater (no biological activity), which may explain their persistence in groundwater.

• ***Contaminant levels*** and concentration processes may differ significantly depending on the transfer conditions and the corresponding circulation velocities. The role as a filter played by soil is decisive and its has been observed that when water flows through soil (deep infiltration, sub-surface flows and drainage), pesticide concentrations are generally much lower than those noted in runoff water (by a factor of 10 to 1 000 *[Voltz and Louchart, 2001]*). On the other hand, pesticides are likely to persist longer (chronic pollution) due to the slower flow velocities transporting substances to the receiving aquatic environments in a more progressive and delayed manner.

1.2.6 Transfer of suspended solids

Suspended solids are solid particles that may be organic and/or mineral, are generally very small, are transported by water and cause its turbidity. Though not, strictly speaking, a contaminant released by humans in the environment, suspended solids also contribute to degrading aquatic ecosystems by reducing the penetration of light, clogging the habitats of benthic fauna and spawning grounds, and causing sedimentation in water bodies. They are also a factor in modifying the chemical composition of aquatic environments by transporting potential pollutants (bacteria, adsorbed contaminants including phosphorous, pesticides and heavy metals). Standards for drinking water also take this aspect into account to avoid any health risks (turbidity is limited to 2 FNU (formazine nephelometric unit). Suspended solids are both an intrinsic factor in the degradation of water quality and a vector for contaminants.

It should be noted that situations affected by the transfer of suspended solids are also likely to be confronted with problems in terms of organic matter (including organic nitrogen), phosphorous and adsorbed pesticides. That is why these various categories of contaminants were grouped according to the solutions recommended when creating buffer zones *[see Section 2.3.]*.

In farming areas, suspended solids are due in large part to the separation and transport of soil particles caused by hydric erosion in fields. This process may occur when a soil that is structurally unstable (low clay and organic-matter content) and poorly covered is exposed to rain. The rain water decomposes the soil into fine particles (splash effect of the raindrops) that can be easily carried off by the runoff water, even on very slight slopes. On steeper slopes and when runoff water is concentrated by the topography (including for saturation excess overland flow), the water can acquire sufficient velocity to detach and transport soil particles of various sizes, to the point of creating more or less deep ditches in some cases. Similarly, the leaching processes at work in certain soils may also result in suspended solids in drainage water or in deep percolation processes. In these cases, the particles in question are generally very small (clay particles).

On the other hand, areas that slow the flow velocities (presence of a rough cover, flat areas) enable sedimentation of the suspended solids in part or in whole (the larger particles are more easily intercepted than the smaller, with as a result grain-size sorting from upstream to downstream). The transfer of suspended solids and of adsorbed contaminants is strongly influenced by the topography, soil use (cover) and, generally speaking, by how the landscape is organised (links between landscape components, infrastructure to reduce erosion, hydraulic installations).

1.3 ■ Assessment phase

The process leading to the creation of buffer zones may require up to five distinct but complementary steps, with degrees of observational detail and requisite field data that increase with the scale of the territory concerned *[Fig. 23]*.

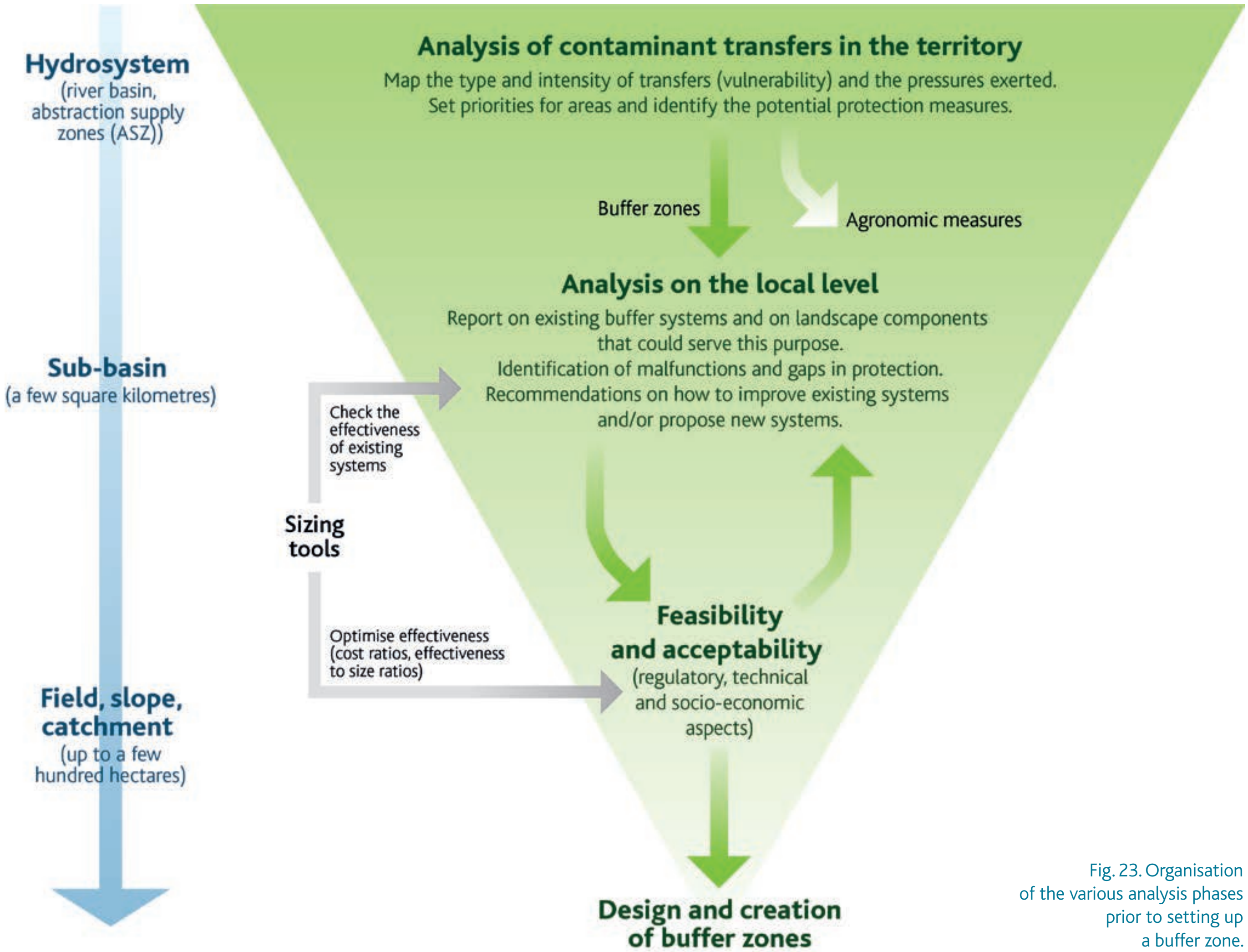


Fig. 23. Organisation of the various analysis phases prior to setting up a buffer zone.

On the hydrosystem level (river basin, abstraction supply zones):

- **identification of the problem by monitoring water quality**: type(s) of contaminant(s) found in the aquatic environment, frequency, concentration levels, etc.;
- understanding and characterising the transfer processes at work *[see Section 1.2.1.]* by running a **vulnerability analysis**, to determine the agricultural/pedological/climatic conditions most sensitive to contaminant flows, detect how the transfers reach the aquatic environments and set priorities for the areas requiring work;
- **characterisation of farming practices (analysis of pressures)**: usage conditions of the substances causing the contamination of aquatic environments, doses applied or spread, treatment periods, fields or farms concerned, etc., to which factors in the socio-economic context may be added to determine the potential flexibility in terms of changing work habits and agricultural systems.

On the level of the sub-basins identified as the most vulnerable, it is necessary to identify the buffer systems that already exist and the landscape components that can act as buffer systems. This includes the identification of malfunctions, gaps in protection and the drafting of recommendations on the basis of an in-depth study of the transfers and paths taken by water in the specific catchment.

On the level of the intercepted fields, slopes and catchments, the preliminary study must quantify sufficiently precisely the volumes of water likely to flow through the buffer zone in order to determine its size taking into account the desired effectiveness.

The first three steps in the study are generally carried out well in advance of the actual creation and are not necessarily specific to a given project. They are often fairly generic for projects to protect water abstractions and aim, on the one hand, to identify the areas requiring priority work and, on the other, to adapt corrective measures to the local context (drafting of an action plan). Over the past few years, a number of methods and guides have been developed to assist in running these studies. The following are of particular interest:

- the *Guide on running a territorial analysis of agricultural pressures (DTPA)*, drafted by INRA (to be published, currently being tested);
- the various methods used for vulnerability analyses that are highly diverse and more or less complex depending on the desired objective. Table 2 presents a number of qualitative and/or expert methods that have been selected for their operational usefulness.

Table 2. Examples of reference methods to analyse territorial vulnerability.

Method	Mapped transfers	Type of method	Scope
Corpen (1999)*	Runoff, hypodermia, drainage, infiltration	Decision tree	Methods suited to analysis of individual fields
Aquaplaine (Arvalis)*			
Siris-Transfert (Aurousseau *et al.*, 1998)	Superficial transfers (no differentiation)	Table combining four factors to produce a vulnerability score from 0 to 100	
Aquavallée (Arvalis)*	Runoff, hypodermia, drainage, infiltration	Decision tree	River basin
Drastic (Aller *et al.*, 1987) ***Paprika*** (Dorfliger *et al.*., 2004) ***Disco*** (Pochon et Zwalhen, 2003)	Infiltration depending on the type of aquifer (plus runoff in areas with a fractured basement and in karstic environments)	Weighted totals of vulnerability scores coded between 0 and 4	Methods designed for groundwater abstraction supply zones
Adour-Garonne Water Agency (2010)	Superficial transfers (no differentiation)	Weighted totals of vulnerability scores coded between 0 and 4	Methods designed for surface-water abstraction supply zones
Le Hénaff and **Gauroy** (2011)	Runoff (erosion, Horton, saturation excess), hypodermia, drainage	Identification of transfer types by examination in the field	
Catalogne *et al.* (2016)	Runoff (Horton, saturation excess), hypodermia, drainage, infiltration	Vulnerability scores expressed as percentages of risk, with modulation by the climate	Method designed for abstraction supply zones where mixed transfer modes occur

** These three cases concern transfer typologies. The vulnerability is not indicated by a score.*

It was not deemed necessary to go into extensive detail on these initial steps in analysis in that they are well covered in other documents [→]. On the other hand, it is important to stress the importance of the analysis to characterise the hydric functioning of the catchment (or of the abstraction supply zone), that is to determine and locate the preferred paths for contaminant transfer in order to identify the most vulnerable zones. The analysis must determine whether a buffer zone is the most suitable solution (for superficial transfers *[Table 3, p. 31]*) and which sectors require immediate attention. An analysis should produce at least a map showing the transfer typologies (with the dominant transfer mode in each map section) and, ideally, a map showing the vulnerability levels for each type of transfer and indicating the topological relationships between the source fields and the receiving aquatic environments.

→ *http://www.onema.fr/le-centre-de-ressources-captages*

The following analysis phases are more directly concerned with buffer zones. The objective is to make a number of observations in the field in order to advise on improvements to optimise the effectiveness of existing systems or to propose new developments to reinforce the protection of the receiving aquatic environments.

To that end, Irstea has published two complementary guides, one that examines the effectiveness of buffer zones along rivers *[Gril and Le Hénaff, 2010]*, the other that discusses the possibilities of creating buffer zones on slopes *[Gril et al., 2010, Bernard et al., 2014]*. It should be noted that in both cases, these guides address the transfer of plant-protection products, however some elements in the approach are also valid for other types of substances.

1.3.1 Assessment of riparian buffer zones (as seen from the river)

Given that they are mandatory and widely present along watercourses listed by the regulations (Nitrate directive, Good agro-environmental conditions established by the CAP [13], regulations on pesticide-free zones (ZNT) [14]), analysis of existing riparian buffer zones is an unavoidable step prior to proposing new arrangements. The objective is to determine if the zones exist, if they are functional and the causes of any malfunctions.

This analysis *[Gril and Le Hénaff, 2010]* consists of making a number of observations in the field on the riparian buffer zone, the bank on which it is located and the neighbouring fields. It should be carried out on foot along the banks of the watercourses and by climbing the slopes, if necessary, to inspect any tributaries (small watercourses and ditches).

The scale of the analysis should be that of a small river basin (Strahler ranks 1 and 2). It is on this scale that most of the interfaces between farm fields and the hydrographic network are located. However, given the length of watercourses involved, riparian analyses represent a considerable investment in terms of time. Experience has shown that approximately one kilometre of watercourse can be covered per hour. It is necessary to plan in detail the field trip, for example using a photo-map (georeferenced photo with an IGN topographic base, scale 1:5 000 or 1:10 000) that can be used for a preliminary reconnaissance of the most strategic sectors and for marking up the observations.

The elements that should be observed during the analysis are the following:

- the presence and width of riparian buffer zones, and any variations in the zones. A buffer zone is considered to exist if it is at least one metre wide starting from the high point of the bank (including the width of the riparian vegetation if it exists);
- the topography of the buffer zone, of the upstream field and the profile of the watercourse (the edges of the banks, their shapes, the slope and its variations);
- land use, the type of vegetation in the buffer zone (grasses, shrubs, trees, hygrophilic plants indicating humidity) and the type of crop in the upstream field;

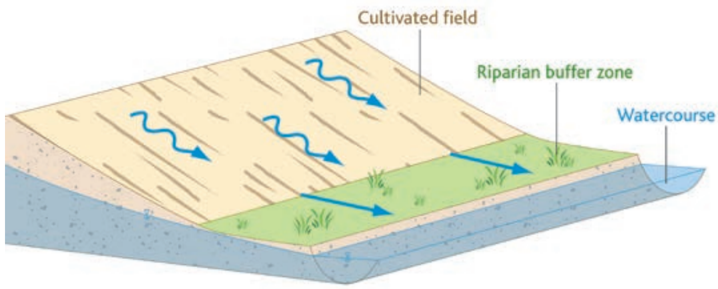
13. The good agro-environmental conditions (GAEC) established by the common agricultural policy (CAP) require a vegetated strip five metres wide along all watercourses covered by the regulations.

14. Pesticide-free zones (ZNT). Regulations governing the use of plant-protection products require a minimum distance from water bodies when applying substances to fields (5, 20, 50 or 100 metres). This distance (indicated on product labels) may be reduced to five metres if special equipment is used (nozzles reducing drift) and if a permanent, vegetated buffer zone exists along the water bodies covered by the regulations.

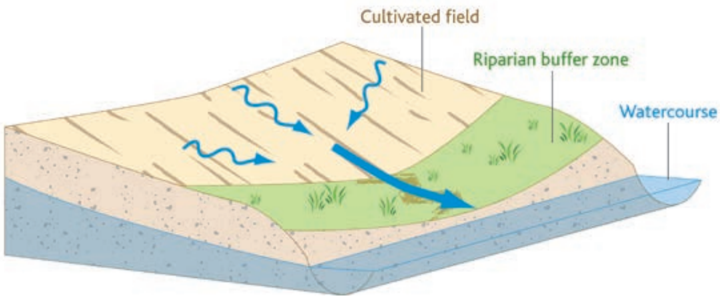
- the hydric functioning of the soil, e.g. capping, hydromorphy, signs of erosion, etc.;
- the paths enabling the concentration of flows and the hydraulic short-circuits such as furrows in the soil, ruts and wheel marks, drainage networks, cemented troughs in wine-growing regions, etc.

All the above information serves as indications concerning the types of flows coming from fields and the potential effectiveness of the buffer zones. Though they may in all cases serve as pesticide-free and non fertilised zones and are definitely of some value, riparian buffer zones may turn out to be relatively ineffective in attenuating hydric transfers of pesticides in certain cases *[Fig. 24]*. That is notably the case:

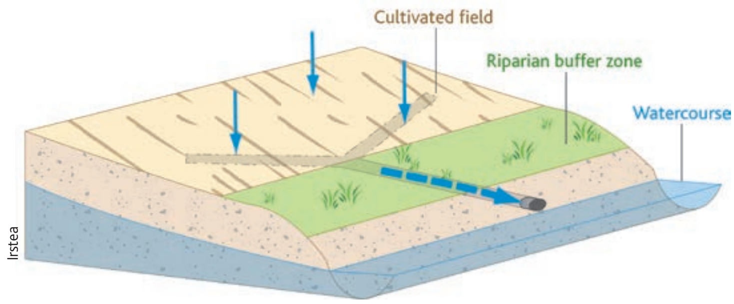
- for poorly protected ditches and small tributaries (hydraulic short-circuits between the upstream field and the watercourse);
- depending on the degree of concentration of flows and the higher risks of saturation at the bottom of slopes;
- depending on the speed at which infiltrated runoff can reach the nearest watercourse.



The soil of the riparian buffer zone is saturated (hydromorphy) due to the proximity of the groundwater with the watercourse (convex bank).
➔ The runoff does not infiltrate.



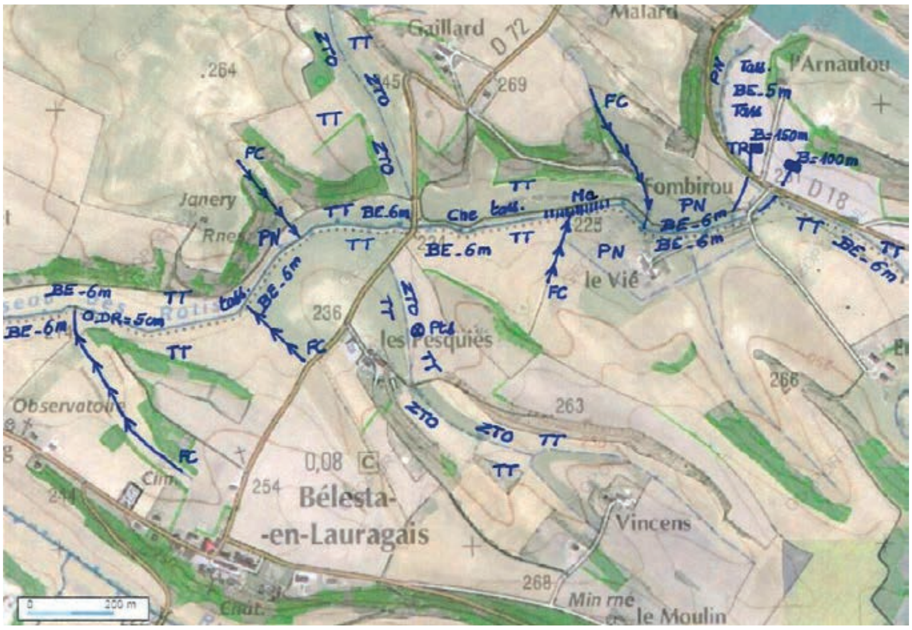
The topography (talweg) and the length of the slope produce a concentrated runoff.
➔ The buffer zone cannot attenuate the runoff.



The water infiltrates in the field (little or no runoff) prior to being transferred to the hydrographic network by a buried drainage system.
➔ The buffer zone is short-circuited.

Fig. 24. Illustration of three factors limiting the effectiveness of riparian buffer zones for surface transfers.

Following the analysis, all the observations should be neatly noted on a map and, if possible, entered into a geographic-information system *[Fig. 25]*). This information will serve during a second phase to assist in making recommendations to improve the effectiveness of existing systems or to add to those systems.



Irstea

Fig. 25. Example of observations noted on a map during a field analysis (the symbols are presented in detail in the guide published by Irstea). The analysis should be carried out during wet weather.

1.3.2 Recommendations on creating additional buffer zones on slopes

This step in the analysis *[Gril et al., 2010]* is generally intended to fill out the analysis on riparian buffer zones and should result in a number of concrete proposals (as such, it contributes to the objective of this guide, but is limited to the transfers of plant-protection products).

The maps produced during the field trips are analysed to identify the areas where the riparian buffer zones are insufficient (or non existent) or where they can simply be reworked to provide better protection for the watercourse. In this latter case, there are a number of potential solutions:

• increase the width of the zone (if necessary, check whether the current width is sufficient using suitable sizing tools), particularly if flows concentrate in a spot (talweg, corner of a field);

• create a simple system to disperse the flows (e.g. fascines) at the interface between the field and the buffer zone, a solution particularly useful for talwegs;

• good upkeep to thicken and homogenise the land cover or to avoid the formation of a mound that concentrates the flow of water. It is necessary to always ensure the best possible connection between the field and the buffer zone;

• removal of minor short-circuits affecting the buffer zone and of paths resulting in the concentration of flows (ruts, ploughing furrows, etc.) through suitable work on the land.

If the effectiveness of the buffer zone is severely curtailed by unfavourable conditions (hydromorphic soil, major concentration of flows, short-circuits), additional observations will be required to determine the potential for creating buffer systems higher up on the slope. The necessary observations are similar to those mentioned above, i.e. the degree and organisation of concentrated flows, hydromorphy, the presence of buried drainage systems, etc.

For each situation, it should be possible to devise recommendations on selecting and positioning new buffer systems *[Fig. 26]*. To that end, the second guide published by Irstea *[Gril et al., 2010]* proposes a decision tree to assist users in selecting the type of buffer zone best suited to the context, as a function of criteria noted in each field or set of fields (topography, cropping techniques, soil characteristics, etc.). This step may produce a set of pre-proposals *[Fig. 27]*.

Fig. 26. Except from the decision tree proposed by Gril *et al.* (2010).

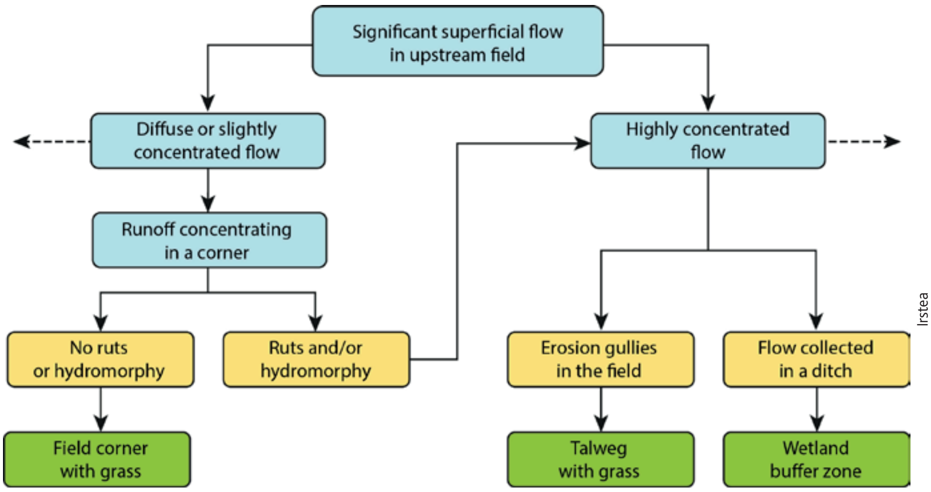
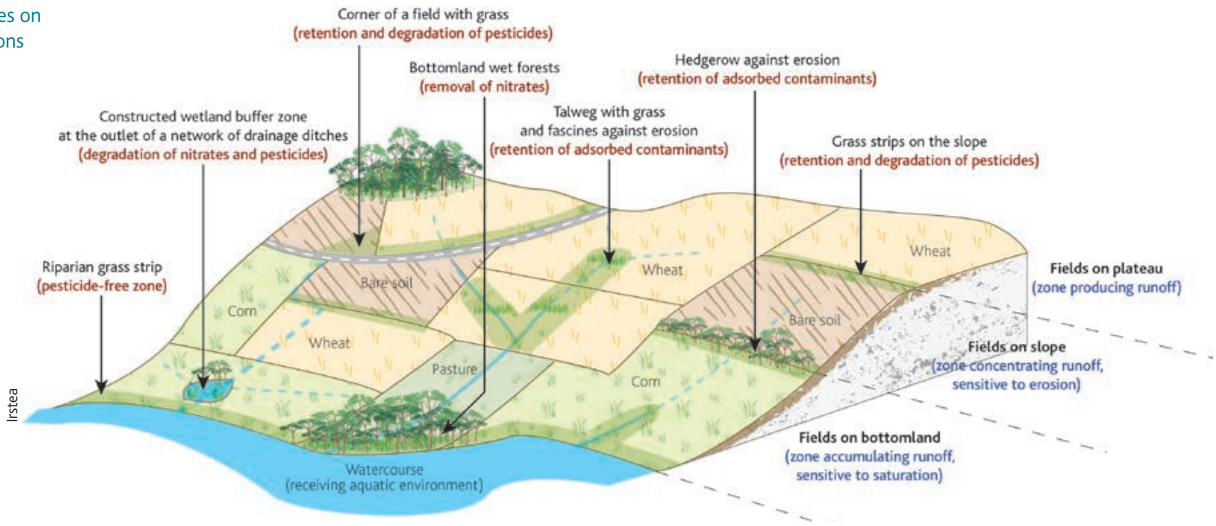


Fig. 27. An example of buffer zones on a farmed slope. An array of solutions may be proposed to manage the various problems encountered.



On the basis of the proposed scenarios, it is necessary to determine the potential solutions offered by the territory (existing spaces between fields, areas of little farming value or already abandoned, etc.) in order to position the complementary systems while taking into account regulatory constraints, technical feasibility (available land, favourable pedology and topography, access, etc.) and socio-economic constraints (costs, acceptability, upkeep and management considerations, etc.), as well as any additional benefits gained (agreeable landscaping, consolidation of ecological networks and preservation of biodiversity, use of biomass, backup land for irrigation, etc.).

This study phase must be carried out collectively bringing together all stakeholders concerned by the project, in particular the farmers (who should also participate in the analysis phase), in order to produce a project that is accepted by all. At this stage, the shift from the analysis to the actual creation phase is already well under way because the project for the buffer system must take into account, at least in approximate terms, the design and sizing rules specific to each type of system.

1.3.3 Sizing considerations

During the creation of a buffer system, the objective of the sizing phase is to determine the dimensional characteristics (width, total surface area, volume) required to reach the targeted level of effectiveness. In other words, an effort is made to limit the land used to a minimum in order to reduce the cost while ensuring effective protection of water resources. This is often a useful topic to encourage discussions among stakeholders in the area and encourage co-construction of the project *[Tournebize* et al.*, 2012]*. The calculations made can also be used to check the effectiveness of any existing systems in the area, e.g. the riparian buffer zones required by the regulations.

The applicable sizing rules differ from one type of system to another, depending on the desired effects. From a strictly hydrological point of view, they generally take into account two aspects:

- the volumes of water intercepted by the system over time from the upstream fields;
- the characteristics specific to the buffer system (pedology, dimensions and layout, roughness caused by the vegetation, hydraulic characteristics of water bodies, etc.).

In the first case, a relatively complete hydrological study is required to quantitatively assess the flows of water over time or depending on the season (compared to a vulnerability study that is generally limited to a qualitative assessment of risk). It is necessary to use more or less complex models, ranging from a simple hydric study up to hydrological and hydrodynamic models, that require a more or less demanding set of data (rainfall, soil characteristics, topography, land use and cropping techniques, etc.), but are relatively accessible for the small areas under consideration (fields or slopes). Various instruments for hydrological monitoring may also be used to complement the models or even to replace them in order to obtain more precise information on the quantities of water likely transit through the buffer zone.

In the second case, other models addressing the functioning of the buffer zone are used, notably hydraulic models. In conjunction with those models, mechanisms to attenuate and dissipate contaminants in the buffer zone may be employed, which may require the analysis of hydrochemical and/or biological processes.

A number of operational tools (software, charts, etc.) have been created over the past few years to run the necessary calculations for the different types of buffer system. These tools, if they exist, are mentioned in the next section and are presented in detail in the annexes. If they do not exist, **rough estimates of their effectiveness may be provided empirically using experimental results, on the condition that said results are representative of conditions comparable to those observed for the given project.**

It should be noted that the issue of representativeness also exists for "digital" sizing techniques. This is because **the calculations are generally run for a single scenario in which it is difficult to integrate the evolution over time of certain environmental characteristics** (cropping techniques, soil cover, rainfall depending on the season, etc.) **that may influence the results. The choice of the scenario is therefore a critical factor that requires careful study and justification**. Another solution consists of testing, for a given project, a number of scenarios taking into account the variability of environmental characteristics over time. The results will consist of a range of effectiveness values or of sizing characteristics that may be put to discussion (selection of the worst scenario, of the median scenario, etc.). In all cases, it should be noted that a buffer system cannot achieve its full effectiveness under all hydro-climatic conditions and notably under extreme conditions for which it is generally not designed.

2 ■ Operational analysis for selecting and positioning buffer zones to ensure effective protection of water resources

For a given level of effectiveness, the selection of the type and the position of a buffer system (or the combination of several systems) in a river basin must take into account three criteria:

- the type of substance intercepted and the desired effect intended to attenuate its transfer to the receiving aquatic environments;
- the transfer mode (see the five types mentioned in Section 1.2.1.);
- the degree of concentration in the hydraulic flows (caused by the topography, the upstream area drained and the existing hydraulic installations).

There are consequently a number of situations that will be discussed in the various sections of this operational analysis, with recommendations on establishing buffer zones *[Table 3]*.

Table 3. Table for operational analysis

	Diffuse runoff	**Concentrated runoff**	**Drainage (and collection ditches)**	**Sub-surface flows**	**Diffuse infiltration to groundwater**
Nitrates	None or negligible	None or negligible	Recommended buffer zones *[→ Section 2.2.2.b.]*	Recommended buffer zones *[→ Section 2.2.2.a.]*	Buffer zones not suitable
Suspended solids **Organic matter** (organic nitrogen) **Adsorbed contaminants** (particulate phosphorous, adsorbed pesticides)	Recommended buffer zones *[→ Section 2.3.2.a.]*	Recommended buffer zones *[→ Section 2.3.2.b.]*	Recommended buffer zones (not documented) *[→ Section 2.3.2.c.]*	None or negligible	None or negligible
Dissolved pesticides	Recommended buffer zones *[→ Section 2.4.2.a.]*	Recommended buffer zones *[→ Section 2.4.2.b.]*	Recommended buffer zones *[→ Section 2.4.2.c.]*	Buffer zones not well suited	Buffer zones not suitable

Generally speaking, the buffer systems must be capable of intercepting the flows. Obviously, it is possible to intercept only those flows that are superficial or sub-surface flows.

For this reason, buffer zones are most commonly used to protect surface aquatic environments (watercourses and water bodies). They may, however, be of use in protecting groundwater if positioned upstream of preferred infiltration sites, e.g. sinkholes in karstic areas (in as much as the sinkholes are supplied by superficial flows, as is often the case). The procedures are identical in both cases and will not be distinguished in the discussions below. On the other hand, buffer zones are never a suitable solution for transfers occurring due to diffuse infiltration [15], for which agronomic methods and techniques are the only sensible solution

2.1 ■ Note to readers

The sections below provide reference data on the effectiveness of buffer zones against various transfer modes of farm substances to receiving aquatic environments. **Use of these data requires care and they must be analysed in light of several criteria concerning the conditions surrounding the creation of the buffer system and its sizing**. The data concerning system effectiveness are essentially derived from experiments that depend, by definition, on the specific experimental conditions (agricultural/pedological/climatic conditions) and on the studied substance, in particular for the large group of plant-protection products. Consequently, readers must be aware of the limits to the validity of the data presented. **It is deemed essential to read the annexes (and the footnoted literature) that discuss in detail the reference data.**

Effectiveness is also heavily dependant on the variability of climate and hydrological conditions over time (seasonally or from one year to the next). A buffer system may not have a constant level of effectiveness with respect to the situation for which it was sized, depending for example on the level of rainfall in a given year. It should be noted here that buffer zones are not designed to handle extreme events, but are rather intended for what are considered “ordinary” flows in a rural environment.

Finally, a further important consideration concerns the positioning strategy for buffer systems in the river basin. The strategy will not always be based solely on the criteria presented in this guide. Factors dealing with the technical feasibility and the acceptability of the project may skew the decision process, notably in terms of the costs involved, upkeep and management constraints, the land required as well as local conditions impacting the process (notably the topography and pedology). In most cases, it is advised to study several solutions, to weigh the advantages and disadvantages of each, and to discuss them among the stakeholders in order to arrive at a consensus (but without neglecting the primary objective of effective protection!), often the prerequisite for the success of a project.

15. Except in cases where the objective is to preserve the land or to set up wooded or grass spaces intended to act as “dilution surfaces”.

2.2 ■ Controlling nitrate transfers using buffer zones

The mechanisms governing nitrate transfers to surface and groundwater aquatic environments were discussed in Section 1.2.2. Here, it should simply be noted that there are three types of transfer, 1) diffuse infiltration to deep groundwater (which will not be discussed in this document for the reasons mentioned above), 2) flows collected by buried drainage systems and 3) sub-surface flows at a low depth in the soil or via superficial groundwater (notably in areas with a crystalline substratum), that are likely to reach a watercourse

2.2.1 Targeted processes and operation of buffer zones to control nitrate transfers

The use of buffer zones to control nitrate transfers attempts to encourage (jointly or separately) two attenuation mechanisms described below.

➔ **Absorption of water and nutrients by the roots of the existing vegetation.** In this case, trees and shrubs are the best solution due to the greater depth of their roots that enable them to draw water and nutrients from a larger segment of the soil than herbaceous plants. This is typically the case for **hedgerows on slopes** *[p. 12]*, positioned perpendicularly to the slope to intercept sub-surface flows or hedgerows and riparian vegetation at the foot of slopes to draw nutrients from the water table. It should be noted, however, that the nitrogen absorbed by plants may be released to the environment when the plant dies or becomes senescent (falling leaves, rotting roots), in the form of organic matter that will in turn mineralise more or less progressively [16]. Removal of the biomass produced, e.g. by trimming the trees to obtain ramial chipped wood (RCW) or firewood) may be a means to reduce the released nitrogen. Even if no biomass is removed, a beneficial effect may be achieved due to the regulation of nitrate flows by the assimilation/restitution/mineralisation cycle. One of the limits to this solution is that the main period for nitrate transfers is from November to March (the period of hydric surpluses), which is also the rest period for the vegetation, i.e. when it requires less water and fewer nutrients). For this reason and in spite of a less developed root system, herbaceous plants, notably grasses, have the advantage of being active most of the year (when the temperature exceeds 5°C). It is therefore advised to combine the herbaceous, shrub and tree stages.

➔ **Denitrification**. In this case, anoxic conditions (saturated with water) must be more or less permanent in the buffer zone. Such conditions exist in **water bodies** *[p. 15]*, but also in **wet patches on slopes, pastures and wet woodlands in bottomland** *[p. 12]* that should be preserved because they consist of hydromorphic soil that is saturated part of the year. The other conditions are the presence of organic matter and, to a lesser degree, favourable pH and temperature conditions for biological activity. Consequently, for flows through a hydromorphic soil saturated with water, it is important that the flows take place in the horizons containing high levels of organic matter, which implies that the water level is fairly close to the surface and/or that there is a thick layer of litter (notably in woods). The existing vegetation can also participate in regulating nitrate flows by drawing off a certain quantity of the nitrates. During the summer, however, evapotranspiration may dry the soil to some degree and temporarily inhibit the denitrification process. That being said, the two mechanisms are not contradictory, but rather complementary depending on the season (absorption by the roots in the summer and denitrification during the winter *[Fig. 28, next page]*). Finally, it should be noted that along the watercourse, the riparian vegetation *[p. 12]*) and any adjacent wetlands also play an important role in attenuating nitrate flows through denitrification (the reduction in nitrate flows may reach 95% *[Jordan* et al.*, 1993, Sanchez-Perez* et al.*, 1999]*).

16. This is the targeted mechanism in agroforestry by which nitrogen deep in the soil is brought to the surface and made available for crops, thus limiting nitrogen losses due to leaching below the root level.

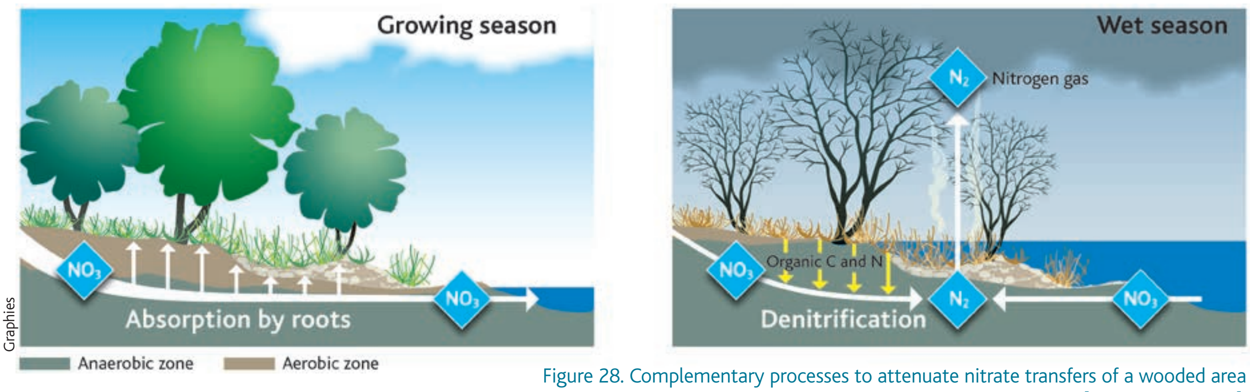


Figure 28. Complementary processes to attenuate nitrate transfers of a wooded area in bottomland, depending on the season *[see Maridet, 1995]*.

2.2.2 Selecting the type of buffer and positioning it on a slope depending on the type of nitrate transfer

→ Sub-surface flows

Recommended type of buffer zone	Woodlands and wet pastures	Hedgerows
Position	Generally in hydromorphic bottomland, near watercourses.	On slopes, laid out perpendicular to the slope.
Process	Denitrification and absorption by roots.	Absorption by roots.
Effectiveness	The reduction varies over time, depending on the saturation conditions, the intercepted water volumes and the velocity of flow in the soil, from 20% to 100% for widths ranging from 1 metre to 150 m *[see Corpen, 2007b]*. Maridet (1995) signals a high level of effectiveness (> 80%) in eliminating nitrogen by riparian vegetation starting at widths of 5 metres or more *[see Annexe II for more information]* [17].	Variable, depending on the season and the type of vegetation. Theoretically zero over the long term [18].
Suggested reading	Maridet (1995), Bidois (1999), Montreuil (2008), Caubel (2001), Grimaldi et al. (2012).	Viaud (2004).
Useful information	The position at the bottom of the slope, along the watercourse, is a good one because most of the sub-surface flows will transit through the butter zone. In addition, when the buffer zone covers both the bottom of the slope and the bank, the water from the watercourse is also intercepted during high-water periods. That being said, the role played by hydromorphic zones located on the slopes should not be neglected.	Hedgerows are also positive factors for other types of contaminants *[see Sections 2.3. and 2.4.]*.

Table 4

→ Drainage

Recommended type of buffer zone	Vegetated water body (constructed wetland buffer zone (CWBZ))
Position	Between the outlets of the drainage system (or of the collecting ditches) and the watercourse.
Process	Denitrification and absorption by roots.
Effectiveness	Variable reduction, ranging from 20% to 100%, depending on the hydraulic residence time and the climatic conditions. Mean, annual retention has been estimated at 50% *[see Annexe I for more information]*.
Suggested reading	Tournebize et al. (2015).
Useful information	Interception and retention of the water throughout the drainage period may involve large amounts of water. Consequently, it may be difficult to achieve residence times sufficiently long to remove the entire nitrate load.

Table 5

17. Sizing aspects are not as central in these cases as for "constructed" systems. This is because it is difficult to determine the truly effective surface area, i.e. that in which soil saturation is sufficiently permanent to result in denitrification

18. Sources indicate that absorption of nitrates by a hedgerow can be significant in the spring (approximately 75% or even 100%, depending on the authors), but that 60% to 90% of the absorbed nitrogen is returned to the surface as organic matter in the fall (Ranger et al., 1995), with subsequent mineralisation of approximately 4% of the litter produced annually (for a riparian forest, Clément, 2002). The net result would appear to be positive over the short term, but will theoretically be zero over the long term (unless biomass is removed) and may even lead to an increase in nitrogen levels in the soil near the hedgerow compared to nearby cultivated fields (Mette and Sattelmaher, 1994).

2.3 ■ Controlling transfers of suspended solids, organic matter and contaminants adsorbed by buffer zones

As noted in Section 1.2.6., transfers of suspended solids and of the adsorbed contaminants (including phosphorous and pesticides with a high Koc coefficient) are caused primarily by runoff, when the water carries the soil particles to the aquatic environments. The role of buffer zones is to intercept the runoff water and retain the transported sediment, but also to limit soil pick-up and ravining along the water path.

2.3.1 Targeted processes and operation of buffer zones to control transfer of suspended solids

Buffer zones attempt to limit the transfer of suspended solids by **sufficiently reducing the flow velocity to induce sedimentation of the soil particles** carried by the runoff water. The primary criterion governing effectiveness is the roughness of the cover and the degree to which it can resist and slow the flow of water. The best solution is a high density of stalks in the soil cover. Care should be taken to ensure the homogeneity of the cover to avoid the development of preferred paths that would reduce the overall effectiveness of the system. The secondary criterion is infiltration. This reduces the volume of runoff and its capacity to carry the sediment, even to the point of complete infiltration and retention of 100% of the solids. Finally, the layout of the system can be designed to reduce the slope over the zone or even create a slight counter-slope in order to slow the runoff.

In light of the desired effect, i.e. control erosion and limit the flow of suspended solids, selection of the type of buffer system may differ depending on the volume of water and the sediment load. **Grass-based systems** *[p. 10]* **are suitable primarily for diffuse, erosive runoff (a sheet of water), where water volumes and the sediment load are small, otherwise the system risks being regularly submerged (flattened vegetation) and/or damaged by the deposited sediment**. Over time, a mound may form along the border between the field and the buffer zone. The water will attempt to circumnavigate the obstacle, which may create a preferred path, contrary to the desired result. Consequently, it is important to ensure the best possible continuity between the field and the grass strip, notably by regularly removing the mound of earth. Similarly, a ploughing furrow at the interface between the field and the buffer zone may divert the water to a low point, thus concentrating the flow in a small part of the zone.

In situations where there is concentrated runoff and linear erosion and/or a high sediment load, a more resistant cover will be required to intercept the flow of water and sediment. Ligneous systems such as **dense hedgerows** *[p. 12]* and **fascines** *[p. 13]* are the most suitable solutions, where the first has the additional advantage of providing good infiltration. In both cases, careful initial work and regular upkeep are indispensable if these systems are to function correctly. To achieve optimum effectiveness, a combination of the techniques with a grass strip positioned downstream of the ligneous system is advised. The hedgerow (or fascine) will slow and disperse the runoff while retaining any coarse materials, whereas the downstream grass strip will serve to decant the finer particles [19] (bearing most of the contaminants) without being overwhelmed by the sediment. Finally, **planting grass in a talweg** *[p. 11*] (over a significant longitudinal distance, i.e. parallel to the flow) is an effective solution not only to intercept and slow diffuse, erosive runoff arriving from the slopes, but also to avoid linear erosion in the talweg itself.

The objective of the systems mentioned here is to block the sediment while letting the water flow. They are relatively "light" systems that should be installed fairly high on the slopes. Further downstream, more work-intensive techniques (planted embankments and ditches, sedimentation basins) may be used to temporarily store and/or divert the water in order to protect specific spots.

19. Experiments have shown that most of the sediment load is intercepted in the first few metres of a grass strip. However, there is a differentiation according to the grain sizes, with sedimentation of the coarse particles whereas retention of the finer particles (clay) requires a much greater width.

2.3.2 Selecting the type of buffer and positioning it on a slope depending on the type of transfer of suspended solids

→ Diffuse, erosive runoff (a sheet of water)

Sediment load	Low	Moderate to high
Recommended type of buffer zone	**Grass strips**	**Dense hedgerows**
Position	On slopes, laid out perpendicular to the slope.	
Process	Reduction of flow velocities and of the water volume (infiltration).	
Effectiveness	Reduction of 40 to 100% for widths from 1 to 300 m and slopes from 0.1 to 16% *[see Corpen, 2007a, see Annexe III for more information]*.	Reduction of 74 to 99% *[according to the experimental results obtained by Ouvry et al. (2012), see Annexe IV for more information]*.
Suggested reading	Corpen (2007), Ouvry *et al.* (2010)	Dabney *et al.* (1995), Ouvry *et al.* (2012)
Useful information	In addition to retaining sediment, staging of the various systems on the slope is a means to regulate the flow velocity and reduce the risks of incision downstream. Their infiltration capabilities, that are relatively significant and stable over time compared to cropped fields (approximately 50 to 100 mm/h), will reduce runoff volumes in the river basin.	

Table 6

→ Concentrated, erosive runoff (traces of linear erosion)

Sediment load	Low to moderate	Moderate to high
Recommended type of buffer zone	**Talweg with grass**	**Dense hedgerows and fascines**
Position	Along the water path (generally in a talweg with fairly steep sides).	Perpendicular to the flow (generally in a talweg).
Process	Reduction of flow velocities and of the water volume (infiltration) and limitation of incision risks.	
Effectiveness	The limitation of incision risks provided by a grass cover is effective up to flow velocities of 0.7 m/s to 2.0 m/s *[data from Ouvry* et al.*, 2010]*. The effectiveness in retaining sediment is similar to that of grass strips *[see Annexe III]*.	Reduction of 74 to 99% *[according to the experimental results obtained by Ouvry* et al.*, 2012), see Annexe IV for more information]*.
Suggested reading	Corpen (2007), Ouvry *et al.* (2010)	Ouvry *et al.* (2012)
Useful information	Contrary to other systems, a talweg with grass must often be created through cultivated fields, which can create significant difficulties for farmers. Alternative techniques, such as double sowing in the talweg, may replace the grass, but are not permanent solutions.	The progressive accumulation of sediment upstream of the buffer will modify the slope and create a zone of calmer water that is favourable for sedimentation.

** Except fascines.*

Table 7

→ Drainage

The transfer of suspended solids by drainage water is not discussed here because there is very little available literature on solutions to attenuate the phenomenon. However, it may be assumed that the solutions are similar to those for the transfer of nitrates and pesticides through drainage, namely the creation of a water body such as a constructed wetland buffer zone (CWBZ) or vegetated ditches to significantly reduce flow velocities and encourage sedimentation.

2.4 ■ Controlling transfers of dissolved pesticides using buffer zones

The mechanisms governing dispersal of pesticides in the environment are described in Section 1.2.5. The adsorbed fraction, which shares the fate of the soil particles, was discussed in the previous section concerning transfers of suspended solids via erosive runoff *[see Section 2.3.]*. The dissolved fraction is discussed here.

2.4.1 Targeted processes and operation of buffer zones to control transfer of dissolved pesticides

On the basis of the information presented in Section 1.2.5., it is clear that the objective in controlling the transfer of dissolved pesticides using buffer zones is to attenuate the most rapid and the most concentrated transfers. The aim is to optimise the contact time between the water, the soil and the vegetation in order to enhance the degradation of the substances.

When runoff is diffuse or moderately concentrated, the main objective of a **grass** *[p. 10]* or **ligneous buffer zone** *[p. 13]* is to intercept the flows and enable their infiltration in the soil. The contact of the soil with the substances carried by the water will, to a large degree, retain and/or degrade the substances. The criteria governing effectiveness are therefore those facilitating good infiltration (soil permeability, enhanced by good root systems of the existing vegetation), combined with a reduced flow velocity (roughness and homogeneity of the cover, layout of the buffer system) [20], but also those that encourage a high level of biological activity in the system (high level of organic matter). Given the targeted process, hydromorphic zones are not seen as favourable for the creation of this type of buffer zone. The presence of water close to the surface would significantly limit the infiltration capacity of the system. Similarly, compacting the soil by the repeated passage of farm equipment or of livestock could considerably reduce the effectiveness of the system, which is why a buffer zone should not be used as the headland of a field.

When flows are hydraulically concentrated, whether in the form of runoff or of drainage water collected by a network of ditches, a **water body** *[p. 15]* is generally the best solution for a buffer system. In this case, it is the residence time of the water (and of the contaminants transported) that is the main criterion for effectiveness in that it provides the various degradation processes, biological or abiotic, with the necessary time. Suitable vegetation for wetlands (macrophytes such as reeds, spike-rush or cattail) is an essential factor to ensure correct functioning of this type of system, in that it:

- encourages biological activity (input of organic matter, release of oxygen in the root system, support for biofilm formation);
- slows the flow and increases the contact time between the water, the vegetation and the substrate of the water body.

A potential addition to the previous solution is the use of **ditches** *[p. 14]* as a buffer system. Similar to water bodies, the characteristics of ditches capable of slowing the flow of water and even temporarily retaining it (shape and slope, roughness created by vegetation, check dams) are highly beneficial in limiting the flow of contaminants.

The type of substrate is also important. Plants (notably macrophytes), fine sediment and a high percentage of organic matter are all positive factors, to varying degrees, in fixing the plant-protection products and stimulating the biological activity required for their degradation *[Kao et al., 2002, Margoum et al., 2003]*.

On the other hand, buffer zones are rarely used to control the transfer of pesticides via sub-surface flows. This is because the interception of the contaminated water rarely produces good results unless the water flows in the horizons with the highest levels of organic matter.

20. Note that there are similarities in the targeted processes intended to control dissolved pesticides and pesticides adsorbed to suspended solids.

2.4.2 Selecting the type of buffer and positioning it on a slope depending on the type of transfer of dissolved pesticides

→ Diffuse flow

Recommended type of buffer zone	**Grass strips or hedgerows**
Position	On a slope, positioned perpendicular to the flow, or along ditches and small watercourses (streams).
Process	Infiltration, retention and degradation of substances in the soil.
Effectiveness	Reduction rate generally greater than 50% and often greater than 90%, but highly dependent on correct sizing of the buffer *[see Annexe V for more information]*.
Suggested reading	Carluer *et al.* (2011), Dosskey *et al.* (2011), Carluer and Lauvernet (2014), Passeport *et al.* (2014).
Useful information	The increasing age of the buffer and correct upkeep will result in a more dense cover and progressive increase in the organic matter in the soil, favourable factors for biological activity and better degradation of the substances.

Table 8

→ Moderately concentrated flow (small talweg, corner of a field)

Recommended type of buffer zone	**Talweg or field corner with grass**
Position	Along the water path.
Process	Infiltration, retention and degradation of substances in the soil.
Effectiveness	The degree of effectiveness may be determined using the same tools as those mentioned above for grass strips or hedgerows. In this case, it is however advised to use the sizing method proposed by Dosskey *et al.* (2011) *[see Annexe V for more information]*.
Suggested reading	Carluer *et al.* (2011), Dosskey *et al.* (2011), Carluer and Lauvernet (2014).
Useful information	Contrary to grass strips, the specific layout of these grass buffers, whose greatest dimension is positioned parallel to the flow of water, requires the largest possible effective width in order to intercept flows using the smallest possible surface area.

Table 9

→ Concentrated runoff or drainage collected by the network of ditches [1]

Recommended type of buffer zone	**Vegetated water body** (constructed wetland buffer zone (CWBZ))
Position	To optimise the degradation function, water from the collection ditches should be diverted to the water body, positioned as close as possible to the drained fields. The hydraulic management system should collect the most concentrated flows in a volume as small as possible. Note that other positions, in riparian buffer zones, have also been experimented for small drainage outlets leading directly to a watercourse.
Process	Retention and degradation.
Effectiveness	Reduction rate in concentrations of approximately 80 to 90%, but can vary (40 to 100%) depending on the substance and the type of buffer system *[based on the experimental results of the Artwet and Phytoret projects, see Annexe VI for more information]*.
Suggested reading	Artwet (2010a and 2010b), Destandeau *et al.* (2013), Phytoret (2014), Tournebize *et al.* (2015), Maillard *et al.* (2011, 2012, 2016), Maillard and Imfeld (2014), Babcsányi *et al.* (2014), Stehle *et al.* (2011), Imfeld *et al.* (2013), Regazzoni *et al.* (2010, 2011, 2013a and 2013b) Vallée *et al.* (2015a and 2015b) for systems set up in riparian buffer zones.rivulaires
Useful information	In a diverted configuration, the hydraulic-management system should open the input gate for the first rains following the application of the substances in order to collect only the water with the highest concentrations of pesticides. The objective is to maximise the residence time (one month is advised) by storing only a limited volume of water. This management system requires the participation of the concerned farmers. The specifications governing opening and closing of the gates must be accepted by the various stakeholders.

Table 10a

Concentrated runoff or drainage collected by the network of ditches [2]

Recommended type of buffer zone	**Ditch with vegetation and/or check dams**
Position	Reworking of existing ditches.
Process	Retention and degradation.
Effectiveness	Reduction rate in peak concentrations of approximately 50% for flow velocities of less than 0.1 m/s *[based on the experimental results of the Artwet project]*.
Suggested reading	Kao *et al*. (2002), Margoum *et al*. (2003), Artwet (2010a and 2010b), Dollinger *et al*. (2015), Dages *et al*. (to be published).
Useful information	Reworking of ditches is advised particularly in areas where their density does not allow for vegetated buffer zones positioned near the fields.

Table 10b

2.5 Multifunctionality, combinations and synergy of buffer systems

The above sections made clear that a number of buffer systems can simultaneously play several roles. That is the case for hedgerows on slopes that will have an effect on both sub-surface, nitrate flows (through draw-off) and on runoff water carrying suspended solids and plant-protection products (through infiltration). Similarly, water bodies may be set up according to layout and management criteria that differ depending on whether the objective is to attenuate the transfer of nitrates or pesticides, however they will have positive effects on both types of contaminants. Other types of buffer system, on the other hand, are more specific in the effects produced, such as bottomland wet forests that are effective for denitrification, but are not well suited to intercept other types of contaminants (at least during the parts of the year during which the soil is saturated).

The combination of different types of buffer system can also be used to reinforce the overall synergy by bringing into play complementary attenuation mechanisms. A typical case is the combination of a ligneous system, e.g. fascines, and a grass-based system, where the first disperses the flow of water and recreates diffuse runoff conditions, enabling the second to better intercept the flow without requiring excessively large dimensions.

Finally, to achieve optimum protection at all times of year and for all types of contaminants, an array of diverse, but complementary buffers systems should ideally be established at various points throughout the river basin. That is the best means to manage the variability of hydrological conditions and farming practices over time. These recommendations are obviously tied to the notion of sustainable regions. The preservation of interstitial spaces and correct landscape organisation are important factors in the equilibrium and resilience of regions, in terms not only of water quality, the main issue here, but also of flood control and erosion, to say nothing of the preservation of biodiversity. All of these environmental services are sources of indirect savings for society as a whole and should be better taken into account in considering the economic and environmental performance of rural areas.

Conclusion

Buffer zones are a development tool for river basins that can provide a particularly useful set of environmental functions for farming areas, e.g. regulation of flows of water, of sediment and polluting substances, but also preservation of biodiversity and of the landscape.

Since the 1990s, the Corpen and subsequently the Buffer-zone technical group have worked to raise awareness concerning these functions by making available operational tools and documents intended to:

- spread information on the functioning and value of buffer zones;
- inform on the methods and best practices for the creation of buffer zones in river basins.

To date, most of the knowledge and technical data collected, based on the work of various research organisations, deals with protecting aquatic environments from nonpoint-source pollution from farms. This guide sums up that information to provide project managers with the knowledge required to select the type of buffer system best suited to their precise situation and needs. This document proposes an analysis method that can be used to easily identify the potential solutions and the degree of effectiveness that may be expected in attempting to control transfers of nitrates, phosphorous, pesticides and suspended solids.

Links to the tools (design and sizing tools for the various buffer systems) available to managers in working on the recommendations made here provide readers with access to further documentary information [➔].

➔ *http://zonestampons.onema.fr/*

Solutions exist for most situations involving the transfer of farm contaminants using the tools mentioned here, however there remain a number of topics that require further study, e.g. the role of ditches in attenuating pesticide transfers. The knowledge gained on these topics may be included in an updated edition of this guide.

Finally, it should be noted that buffer zones are one element in a wider range of more comprehensive solutions that obviously include farming practices using fewer and less inputs, and capable of limiting substance transfers to the fields themselves.

Références bibliographiques

→ AEAG (2010). *Délimitation des aires d'alimentation des captages prioritaires du bassin Adour-Garonne. Méthodologie de cartographie de la vulnérabilité intrinsèque des captages d'eau superficielle*. 28 p.

→ ALLER L., BENNET T., LEHR J.H., PETTY R.J., HACKETT G. (1987). *DRASTIC : a standardized system for evaluating ground water pollution potential using hydrogeological settings.* US Environmental Protection Agency, EPA/600/2-87-036, 455 p.

→ ARTWET (2010a). *Réduction de la pollution diffuse due aux produits phytosanitaires et phytoremédiation dans les zones humides artificielles – Guide d'accompagnement à la mise en œuvre : aspects techniques*. Rapport du projet Artwet (LIFE 06 ENV/F/000133), 111 p.

→ ARTWET (2010a). *Réduction de la pollution diffuse due aux produits phytosanitaires et phytoremédiation dans les zones humides artificielles – Guide d'accompagnement à la mise en œuvre : aspects juridiques économiques et sociaux*. Rapport du projet Artwet (LIFE 06 ENV/F/000133), 62 p.

→ AUBERTOT J.N., BARBIER J.M., CARPENTIER A., Gril J.J., GUICHARD L., LUCAS P., SAVARY S., SAVINI I., VOLTZ M. (2005). *Pesticides, agriculture et environnement. Réduire l'utilisation des pesticides et limiter leurs impacts environnementaux*. Rapport d'Expertise scientifique collective, Inra et Cemagref.

→ AUROUSSEAU et al. (1998). *Éléments pour une méthode d'évaluation d'un risque parcellaire de contamination des eaux superficielles par les pesticides. Étude et Gestion des Sols*, Vol. 5(3), pp. 143-156.

→ BERNARD K., CARLUER N., LE HENAFF G. (2014). *Limitation du transfert hydrique des produits phytosanitaires par les zones tampons : caractérisation de l'existant et propositions de dispositifs correctifs et complémentaires.* Techniques Sciences Méthodes, Vol. 12, pp. 83-99.

→ BABCSÁNYI I., IMFELD G., GRANET M., CHABAUX F. (2014). *Copper Stable Isotopes to Trace Copper Behavior in Wetland Systems. Environmental Science & Technology*, Vol 48, pp. 5520-5529.

→ BIDOIS J. (1999). *Aménagement de zones humides ripariennes pour la reconquête de la qualité de l'eau - Expérimentation et modélisation*. Thèse ENSAR, 263 p.

→ BOIVIN A., MARGOUM C., GUILLEMAIN C., BALL N., CARLUER N., GRIL J-J., GOUY V. (2007). *Water and pesticide transport dynamic in a grass buffer strip*. Wapo conference, Barcelona, 11-13 avril 2007. 6p.

→ CARLUER N., FONTAINE A., LAUVERNET C., MUÑOZ-CARPENA R. (2011). *Guide de dimensionnement des zones tampons enherbées ou boisées pour réduire la contamination des cours d'eau par les produits phytosanitaires*. Rapport Irstea-MAAPRAT, 98 p.

→ CARLUER N., LAUVERNET C. (2014). *Technical report for sizing of vegetative bufferstrips*. Report of the TOPPS-Prowadis Project. Irstea. 17p.

→ CASTELLE A.J., JOHNSON A.W., CONOLLY C. (1994). *Wetland and stream buffer size requirements - a review*. Journal of Environmental Quality, Vol. 23, pp. 878-882.

→ CATALOGNE C., LE HENAFF G., CARLUER C. (2016). *Guide pour l'évaluation de la vulnérabilité intrinsèque aux transferts hydriques de contaminants d'origine agricole dans les aires d'alimentation de captage à transferts mixtes – Présentation de la méthode et exemple d'application*. Rapport Irstea-Onema, 84pp.

→ CAUBEL V. (2001). *Influence de la haie de ceinture de fond de vallée sur les transferts d'eau et de nitrates*. Thèse ENSAR, 155 p.

→ CERDAN O., LE BISSONAIS Y., COUTURIER A., SABY N. (2002b). *Modelling interrill erosion processes in an expert-based runoff and erosion model STREAM*. Hydrological Processes, Vol. 16(16), pp. 3215-3226.

→ CERDAN O., SOUCHERE V., LECOMTE V., A. COUTURIER A., Y. LE BISSONAIS Y. (2002a). *Incorporating soil surface crusting processes in an expert-based runoff and erosion model: STREAM (Sealing and Transfer by Runoff and Erosion related to Agricultural Managment)*. Catena, Vol. 46, pp. 189-205.

→ CLEMENT J.C., PINAY G., MARMONIER P. (2002). *Seasonel dynamics of denitrification along topohydrosequences in three different riparian wetlands*. Journal of Environnemental Quality, Vol. 31, pp. 1025-1037.

→ CORPEN (1997). *Produits phytosanitaires et dispositifs enherbés*. 88 p.

→ CORPEN (1999). *Désherbage - Éléments de raisonnement pour une maîtrise des adventices limitant les risques de pollution des eaux par les produits phytosanitaires*. 149 p.

→ CORPEN (2001). *Diagnostic de la pollution des eaux par les produits phytosanitaires : bases de l'établissement de cahiers des charges des diagnostics de bassins versants et d'exploitations*. 32 pp

→ CORPEN (2003). *Éléments méthodologique pour un diagnostic régional et un suivi de la contamination des eaux liée à l'utilisation des produits phytosanitaires*. 84 p.

→ CORPEN (2007). *Les fonctions environnementales des zones tampons : les bases scientifiques et techniques des fonctions de protection des eaux*. Première édition, 176 p.

→ CORPEN (2007a). *Les fonctions environnementales des zones tampons : les bases scientifiques et techniques des fonctions de protection des eaux*. Annexes 1 à 3.

→ CORPEN (2007b). *Les fonctions environnementales des zones tampons : les bases scientifiques et techniques des fonctions de protection des eaux*. Annexes 4 à 8.

→ DABNEY S.M., MEYER L.D., HARMON W.C., ALONSO C.V., FOSTER G.R. (1995). *Depositional patterns of sediment trapped by grass hedges*. Transactions, American Society of Agricultural Engineers, vol. 38, pp. 1719-1729.

→ DAGES C., BAILLY J-S., DOLLINGER J., LAGACHERIE P., VOLTZ M. (to be published in 2017). *Guide méthodologique pour le diagnostic et la gestion locale des réseaux de fossés en vue de la limitation de la contamination des masses d'eau par les pesticides*. Rapport Inra-Onema.

→ DELETIC A., FLETCHER T.D. (2006). *Performance of grass filters used for stormwater treatment - A field and modelling study*. Journal of hydrology, Vol. 317, pp. 261-275.

→ DESTANDEAU F., IMFELD G., ROZAN A. (2013). *Regulation of diffuse pesticide pollution: combining point source reduction and mitigation in stormwater wetland (Rouffach, France)*. Ecological Engineering, Vol. 60, pp. 299-308.

→ DOLLINGER J., DAGES C., BAILLY J-S., LAGACHERIE P., VOLTZ M. (2014). *Synthèse bibliographique des différentes fonctions des réseaux de fossés aux échelles du fossé élémentaire et du réseau*. Rapport Inra-Onema. 54pp.

→ DORFLIGER N., JAUFFERt D., LOUBIER S., PETIT V. (2004). *Cartographie de la vulnérabilité des aquifères karstiques en Franche-Comté*. Rapport final, BRGM/RP-53576-FR.

→ DORIOZ J.M., WANG D., POULENARD J., TREVISAN D. (2006). *The effect of grass buffer strips on phophorus dynamics - A critical review and synthesis as a basis for application in agricultural landscapes in France*. Agriculture, Ecosystems and Environment, Vol. 117, pp. 4-21.

➔ DOSSKEY M.G., HELMERS M.J. EISENHAUER D.E. (2011). *A design aid for sizing filter strips using buffer area ratio*. Journal of Soil and Water Conservation, Vol. 66(1), pp. 29-39.

➔ ELSAYED O.F., MAILLARD E., VUILLEUMIER S., NIJENHUIS I., RICHNOW H.H., IMFELD G. (2014a). *Using compound-specific isotope analysis to assess the degradation of chloroacetanilide herbicides in lab-scale wetlands*. Chemosphere, Vol. 99, pp. 89-95.

➔ ELSAYED O., MAILLARD E., VUILLEUMIER S., IMFELD G. (2014b). *Bacterial communities in batch and continuous-flow wetlands treating the herbicide S-metolachlor*. Science of the Total Environment, Vol. 499, pp. 327-335.

➔ GRIL J-J., LE HENAFF G. (2010). *Guide de diagnostic de l'efficacité des zones tampons rivulaires vis-à-vis du transfert hydrique des pesticides*. Rapport Irstea-Onema, 46 p.

➔ GRIL J-J., LE HENAFF G., FAIDIX K. (2010). *Mise en place de zones tampons et évaluation de l'efficience de zones tampons existantes destinées à limiter les transferts hydriques de pesticides : guide de diagnostic à l'échelle du petit bassin versant*. Rapport Irstea-MAAP, 42 p.

➔ GRIMALDI C., BAUDRY J., PINAY G. (2012). *Des zones tampons dans les paysages ruraux pour la regulation des pollutions diffuses*. Innovations Agronomiques, Vol. 23, pp. 55-68.

➔ GRIMALDI C., FOSSEY M., THOMAS Z., FAUVEL Y., MEROT P. (2012). *Nitrate attenuation in soil and groundwater under a bottomland tree hedge in a European farming landscape*. Hydrological Processes, Vol. 26, pp. 3570-3578.

➔ IMFELD G., LEFRANCQ M., MAILLARD E., P S. (2013). *Transport and attenuation of dissolved glyphosate and AMPA in a stormwater wetland*. Chemosphere, Vol. 90(4), pp. 1333-1339.

➔ JORDAN T.E., CORELL D.L., WELLER D.E. (1993). *Nutrient interception by a riparian forest receiving inputs from adjacent cropland*. Vol. 22, pp. 467-473.

➔ KADLEC R.H., WALLACE S.D. (2008). *Treatment Wetlands*, 2nd ed. CRC Press, Boca Raton, FL, p.1016

➔ KAO C., VERNET G., LE FILLEUL J-M., NEDELEC Y., CARLUER N., GOUY V. (2002). *Élaboration d'une méthode de typologie des fossés d'assainissement agricole et de leur comportement potentiel vis-à-vis des produits phytosanitaires*. Ingénieries, n°29, pp.49-65.

➔ LACAS J.G. (2005). *Processus de dissipation des produits phytosanitaires dans les zones tampons enherbées - Étude expérimentale et modélisation en vue de limiter la contamination des eaux de surface*. Thèse Cemagref - Université de Montpellier II. 307 p.

➔ LE HENAFF G., GAUROY C. (2011). *Délimitation des aires d'alimentation de captages en eaux de surface et caractérisation de leur vulnérabilité vis-à-vis des pollutions agricoles diffuses par les pesticides – Guide méthodologique*. Rapport Irstea-MEEDDM/MAAF, 55 pp.

➔ MARGOUM C., GOUY V., LAILLET B., DRAMAIS G. (2003). *Rétention des produits phytosanitaires dans les fossés de connexion parcelle-cours d'eau*. Revue des Sciences de l'Eau, Vol. 16(3), pp. 389-405.

➔ MAILLARD E., IMFELD G. (2014). *Pesticide mass budget in a stormwater wetland.* Environmental Science & Technology, Vol. 43, pp. 8603-8611.

➔ MAILLARD E., LANGE J., SCHREIBER S., DOLLINGER J., HERBSTRITT B., MILLET M., IMFELD G. (2016). *Dissipation of hydrological tracers and the herbicide S-metolachlor in batch and continuous-flow wetlands*. Chemosphere, Vol. 144, pp. 2489-2496.

➔ MAILLARD E., PAYRAUDEAU S., ORTIZ F., IMFELD G. (2012). *Removal of pesticide mixtures in a stormwater wetland receiving runoff from a vineyard catchment (Alsace, France): an inter-annual comparison*. International Journal of Environmental Analytical Chemistry, Vol. 92(8), pp. 979-994.

→ MAILLARD E., PAYRAUDEAU S., FAIVRE E., GREGOIRE C., GANGLOFF S., IMFELD G. (2011). *Removal of pesticide mixtures in a stormwater wetland collecting runoff from a vineyard catchment*. Science of the Total Environment, Vol. 409, pp. 2317-2324.

→ MARIDET L. (1995). *Rôle des formations végétales riveraines - Recommandations pour une gestion régionalisée*. Rapport Ministère de l'Environnement, Direction de l'eau. 59 p.

→ METTE R., SATTELMACHER B. (1994). *Root and nitrogen dynamics in the hedgerow - field interface. Consequences for land-use management*. In Proceedings of the 7th International Symposium of CIEC, Agroforestry and Land-Use Change in Industrialised Nation, pp. 275-284. Berlin, Humbolt University.

→ MEYBECK M. (1982). *Carbon, nitrogen and phosphorus transport by world rivers*. Amer. J. Sci., 282, 401-450.

→ MEYER L.D., DABNEY S.M., HARMON W.C. (1995). *Sediment-trapping effectiveness of stiff-grass hedges*. Transactions, American Society of Agricultural Engineers, Vol. 38, pp. 809-815.

→ MONTREUIL O. (2008). *Relation entre l'ordre des bassins versants, l'organisation spatiale et le fonctionnement hydrologique et hydrochimique des zones humides*. Thèse UMR Sol Agro et hydrosystèmes Spatialisation, Équipe Dynamique de l'eau et des éléments associés dans les bassins versants, 242 p.

→ MUÑOZ-CARPENA R., LAUVERNET C., CARLUER N. (2011). *Development and testing of a mechanistic algorithm to calculate the influence of a shallow water table on flow dynamics through vegetative filter strips*. Paper presented at the ASABE Annual International Meeting, Louisville, Kentucky (USA).

→ MUÑOZ-CARPENA R., Parsons J.E (2010). *VFSMOD-W : Vegetative Filter Strip Modeling System*. Available at : http://abe.ufl.edu/carpena/vfsmod/index.shtml

→ MUÑOZ-CARPENA R., PARSONS J.E., GILLIAM J.W. (1999). *Modeling hydrology and sediment transport in vegetative filter strips. Journal of hydrology*, Vol. 214, pp. 111-129.

→ NICOLARDOT B., MARY B., HOUOT S., SETHECOUS S. (1996). *La dynamique de l'azote dans les sols cultivés, la maitrise de l'azote dans les agrosystèmes*. Inra Ed., pp 87-103

→ OUVRY J-F., LE BISSONNAIS Y., MARTIN P., BRICARD O., SOUCHERE V. (2010). *Les couverts herbacés comme outils de réduction des pertes en terre par érosion hydrique : synthèse des connaissances et expérience de la Haute-Normandie*. Fourrages, n°202, pp.103-110.

→ OUVRY J-F., RICHET J-B., BRICARD O., LHERITEAU M., BOUZID M., SAUNIER M (2012). *Haies et fascines pour réduire les effets du ruissellement érosif : caractérisation de l'efficacité et conditions d'utilisation*. Rapport AREAS, 68 pp.

→ PASSEPORT E., RICHARD B., CHAUMONT C., MARGOUM C., LIGER L., GRIL J-J., TOURNEBIZE J. (2014). *Dynamics and mitigation of six pesticides in a "Wet" forest buffer zone*. Environ. Sci. Pollut. Res., Vol. 21, pp.4883–4894 (DOI 10.1007/s11356-013-1724-8).

→ PHYTORET (2014). *Potentiel des zones humides artificielles du Rhin Supérieur pour la réduction des produits phytosanitaires - Guide à destination des prescripteurs et des concepteurs de zones tampons humides artificielles*. 37 p.

→ POCHON A., ZWAHLEN F. (2003). *Délimitation des zones de protection des eaux souterraines en milieu fissuré – Guide pratique*. L'environnement pratique. Office fédéral de l'environnement, des forêts et du paysage, Office fédéral des eaux et de la géologie, Berne, 83 p.

→ RANGER J., COLIN-BELGRAND M., NYS C. (1995). *Le cycle biogéochimique des éléments majeurs dans les écosystèmes forestiers, importance dans le fonctionnement des sols*. Étude et Gestion des sols, Vol. 2(2), pp.119-134.

→ REGAZZONI C., PAYRAUDEAU S., GREGOIRE C. (2010). *Évaluation du potentiel de rétention et de remédiation des flux de produits phytosanitaires dans les eaux de surface par des ouvrages de rétention et de remédiation (OR2)* - Les Ouvrages de rétention et de remédiation (OR2). Laboratoire d'Hydrologie et de Géochimie de Strasbourg, 24p.

→ REGAZZONI C., PAYRAUDEAU S., GREGOIRE C. (2011). *Validation et analyse de la transposabilité des méthodologies d'aménagement et d'implantation de nouveaux ouvrages de rétention et de remédiation (OR2) Alsace, Gard et Seine Maritime*. Rapport d'étape, Laboratoire d'Hydrologie et de Géochimie de Strasbourg, 85p.

→ REGAZZONI C., PAYRAUDEAU S. (2013a). *Guide d'utilisation de l'outil d'aménagement d'ouvrages de rétention et de remédiation (OR2) - Techniques pour la réduction des pollutions diffuses : outil d'aménagement de nouveaux OR2*. Document élaboré dans le cadre du projet ENRHY (2010-2013), Action 12-5-2., 30p.

→ REGAZZONI C., PAYRAUDEAU S. (2013b). *Guide d'utilisation de l'outil d'aménagement d'ouvrages de rétention et de remédiation (OR2) - Techniques pour la réduction des pollutions diffuses*. Document élaboré dans le cadre du projet ENRHY (2010-2013), Action 12-5-2., 30p.

→ SANCHEZ-PEREZ J.M., TREMOLIERES M., TAKATERT M., AACKERER P., EICHHORN A., MAIRE G. (1999). *Quantification of nitrate removal by flooded alluvial zone in the ill floodplain (eastern France)*. Hydrobiologia, Vol. 410, pp. 185-193.

→ STEHLE S., ELSAESSER D., GRÉGOIRE C., IMFELD G., NIEHAUS E., PASSEPORT E., PAYRAUDEAU S., SCHÄFER R.B., TOURNEBIZE J., SCHULZ R. (2011). *Pesticide Risk Mitigation by Vegetated Treatment Systems: A Meta-analysis*. J. Environ. Quality, Vol. 40, pp. 1068-1080.

→ TOURNEBIZE J., GRAMAGLIA C., BIRMANT F., BOUARFA S., CHAUMONT C., VINCENT B. (2012), *Co-design of constructed wetlands to mitigate pesticide pollution in a drained catch-Basin: A solution to improve groundwater quality*. Irrigation and Drainage, n° 61 (suppl. 1), p. 75-86.

→ TOURNEBIZE J., CHAUMONT C., MARCON A., MOLINA S., BERTHAULT D. (2015). *Guide technique à l'implantation des zones tampons humides artificielles (ZTHA) pour réduire les transferts de nitrates et de pesticides dans les eaux de drainage*. Rapport Irstea-Onema, 60 p.

→ USDA-SCS (1972). *National Engineering Handbook*, Part 630 Hydrology. Washington, D.C.

→ VALLEE R., DOUSSET S., BILLET D. (2015a). *Water residence time and pesticide removal in pilot-scale wetlands*. Ecological Engineering, Vol. 85, pp.76-84.

→ VALLÉE R., DOUSSET S., SCHOTT F-X., PALLE C., ORTAR A., CHERRIER R., MUNOZ J-F., BENOÎT M. (2015b). *Do constructed wetlands in grass strips reduce water contamination from drained fields ?*. Environmental Pollution, Vol. 207, pp. 365-373.

→ VIAUD V. (2004). *Organisation spatiale des paysages bocagers et flux d'eau et de nutriments - Approche empirique et modélisation*. Thèse Inra-SAD, 286p.

→ VIAUD V., MEROT P., BAUDRY J. (2004). *Hydrochemical buffer assessment in agricultural landscapes : from local to catchment scale*. Environmental Management, Vol. 34(4), pp. 559-573.

→ VOLTZ M., LOUCHART L. (2001). *Les facteurs-clés de transfert des produits phytosanitaires vers les eaux de surface*. Ingénieries – EAT, numéro spécial Phytosanitaires, pp. 45-51.

→ VOUGHT L.B.M, DAHL J., PEDERSEN C.L., LACOURSIERE J.O. (1994). *Nutrient retention in riparian ecotones*. Ambio, Vol. 23, pp. 342-348.

Notes

Annexes

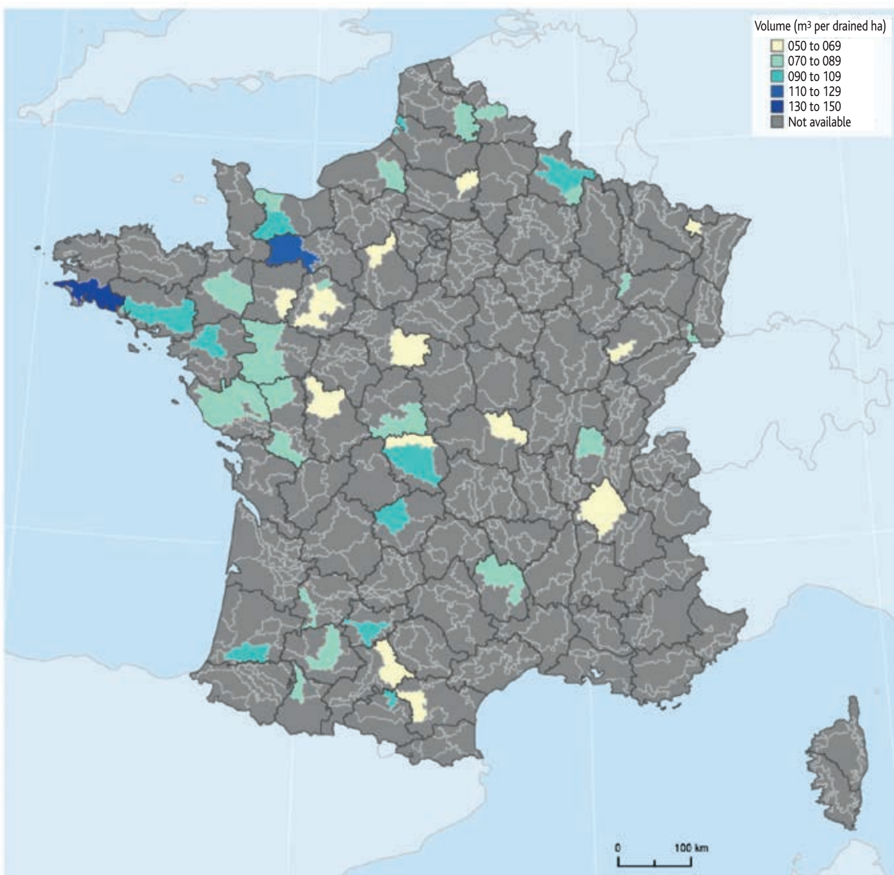
Annex I ■ Information on sizing a constructed wetland buffer zone (CWBZ) to limit nitrate transfers

The information presented here was drawn from the guide published by Tournebize *et al.* (2015), which provides detailed theoretical and practical recommendations on creating a CWBZ in view of purifying the water from a farm-drainage system.

The authors propose sizing information (basin volume) in the form of charts for small farming areas *[Fig. 29]*.

The design criteria for the charts is presented below.

The volume of water exported per drained hectare per day (over the 1950 to 2010 period) was calculated using the SIDRA-RU model developed by Irstea. For each of the small farming areas studied, the soil characteristics required for the model (usable water reserves) were drawn from the data for the existing drainage sectors, considered representative of the local situation.



Irstea

Figure 29. Volumes of constructed wetland buffer zones (cubic metres per drained hectare) recommended by Tournebize *et al.* (2015) to reduce nitrates, calculated for small farming areas.

The assumptions and operating rules for a CWBZ are the following:

• input is limited to 0.5 L/s overall per day (corresponding to maximum inputs of approximately 0.8 to 1 L/s);

• the maximum overflow rate for input flows, due to CWBZ filling by floods with a return period greater than one year, is set at 20%;

• intercepted volumes correspond to the months of November and December;

• the residence time for intercepted volumes is set at seven days, based on the weekly occurrence of floods and a predicted level of effectiveness of 50% for nitrate reduction, deduced from the "tanks in series" approach developed by Kadlec and Wallace (2008) *[Fig. 30]*.

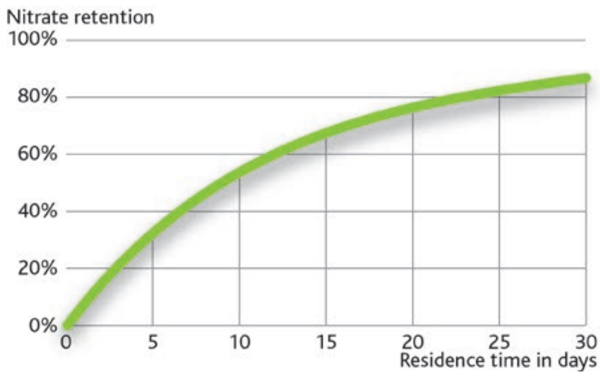


Figure 30. Curve showing reduction rates for nitrate levels (%) as a function of the residence time in a CWBZ, at a constant temperature of 20°C [based on the "tanks in series" approach of Kadlec et Wallace, 2008].

The hydraulic residence time is calculated for a basin with a volume V and an output discharge of:

$$T\ (s) = V\ (m^3) / Q_o\ (m^3/s)$$

On the basis of these assumptions, the estimated volumes (per drained hectare) range from 50 to 150 cubic metres, i.e. for a mean water depth of one metre in the basin, a surface area of the CWBZ equivalent to 0.5 to 1.5% of the area drained upstream. Other sizing rules may be used, e.g. an increase in the residence time to increase the reduction in nitrates, but will obviously make it necessary to run the calculations again using the new parameters.

Even though more work is required on this topic, the authors are of the opinion that a residence time of seven days may be sufficient for a reduction of 50% in the concentrations of plant-protection products (this figure is based on an average of the DT50 values (dissipation time) for a representative set of substances used in large-scale farming. Note that practically speaking, the system layout (bypass mode) and the recommended hydraulic management for plant-protection products means that it is possible to adapt (reduce) the size of the system in view of storing only the most highly concentrated water corresponding to the first rainfall following the treatments in the fields.

Annex II ■ Information on the effectiveness of riparian wetlands (riparian vegetation or bottomland wet forests) in limiting nitrogen transfers

Figure 31, prepared by Maridet (1995) on the basis of experimental data compiled by Vought et al. (1994) and Petersen et al. (1992), illustrates the change in nitrogen levels noted in water as a function of the width of the riparian vegetation. The curve makes clear that there is a major gain in effectiveness from 0 to 5 metres (a reduction of 80%), after which any additional increase in the width produces only a relatively minor improvement in nitrogen reduction. However, given the dispersion of the data points, a width of 10 metres may be deemed more prudent.

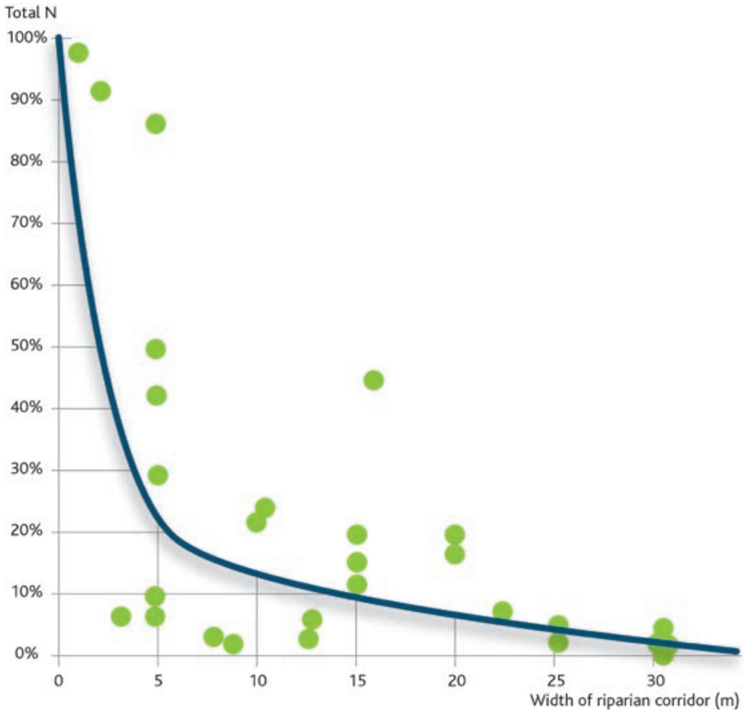


Figure 31. Percentage of the reduction in total nitrogen levels (mineral and organic) as a function of the width of the riparian vegetation *[see Maridet, 1995]*.

Annex III ■ Information on the effectiveness of grass strips in limiting transfer of suspended solids

The Corpen guide, published in 2007, made an in-depth review of the experimental data on the capacity of grass strips to limit the flow of suspended solids. A small number of key figures are republished here.

A summary of the experimental data indicates that **a reduction of 70 to 90% in the flow of suspended solids may be achieved at widths of between 5 and 20 metres** (results vary depending on the experimental conditions, e.g. slope, intercepted volume of water, density of plant stalks and the permeability of the buffer system), where a threshold in effectiveness is reached at a width of 10 metres, above which the gain in reduction is limited *[Castelle* et al.*, 1994]*.

Among the criteria governing effectiveness, the slope would appear to be decisive, which led the USDA Soil conservation service to make a number of recommendations on the topic *[Dorioz, 2006] [Table 11]*.

Table 11

Slope	Recommended width
< 0.5%	11 to 22 m
0.5 to 5%	22 to 36 m
> 5%	36 to 71 m

However, on the basis of a more in-depth study, the Corpen guide indicates that calculations of overall effectiveness must take into account the size of the particles. The guide mentions the work by Deletic (2006), who produced the results presented in Table 12 (for one hour of simulated runoff in a talweg with grass, 5 metres wide) *[Table 12]*.

Table 12

Size class	Mean reduction	Minimum reduction	Maximum reduction
0 to 5.8 μm	45%	18%	86%
5.8 to 22 μm	45%	23%	86%
22 to 57 μm	77%	66%	87%
57 to 180 μm	89%	79%	92%

Meyer *et al*. (1995) also showed that narrow buffer zones with grass, from 0.14 to 0.76 metres in width, retain 90% of coarse sediment (sand) compared to only 20% of clay and silt. **It is clear that grass buffer zones are less effective in attenuating the transfer of fine particles (which also carry most of the pollutants). These results should encourage project managers to add a "safety margin" to the figures commonly observed in the literature**.

Above and beyond this data on system effectiveness, mention should be made here of two modelling tools of use in sizing grass buffer zones and intended to attenuate flows of suspended solids, or in testing different project scenarios for a river basin:

- VFS-mod *[Munoz-Carpena* et al.*, 1999]*, which can be used to test different widths of downstream headlands with grass and assess their effectiveness in terms of infiltration and retention of eroded particles, depending on the soil characteristics and the type of sediment;
- STREAM *[Cerdan* et al.*, 2002a et b]*, which can be used to model runoff and the flows of suspended solids in all the fields of a catchment, taking into account changes in soil surfaces (over a cropping season), and subsequently to test the position of grass covers and to quantify the reduction in liquid and solid flows at different points in the catchment.

Annex IV ■ Information on the effectiveness of dense hedges and fascines (bundled wood) in limiting transfer of suspended solids

The experiments carried out by Ouvry *et al.* (2012) are probably the unique French source of information on the effectiveness of dense hedges and fascines (bundled wood) in limiting the transfer of suspended solids. They resulted in a set of practical recommendations for project managers concerning the position in the catchment, sizing, conditions governing creation and upkeep, costs, etc.

The experiments were carried out in northern France (Pays de Caux) on three dense hedgerows (created specifically for hydraulic purposes) and four fascines positioned at the edge of a field, and using a runoff simulator designed for this type of experiment. The experimental protocol is described in detail in Ouvry *et al.* (2012). The protocol attempted to reproduce representative conditions in terms of the climate, soil (mid-sized silt particles and sand) and buffer systems commonly found in the region.

On each site, two or three trials were run. During each set of trials, a number of parameters were tested:

- the concentration of the injected sediment, ranging from 7 to 28 g/l;
- the specific discharge at the input, ranging from 1.9 to 6.2 l/s per linear metre;
- the grain size of the injected sediment.

The monitored parameters are the input and output discharges, water levels, input and output sediment concentrations, and the grain sizes of the injected sediment and of the deposited sediment.

The results were interpreted in terms of the reduction in flow velocities, infiltration and the reduction in sediment transport. Concerning this last point, Ouvry *et al.* (2012) reached the following conclusions: *"On the whole, the effectiveness of hedgerows and fascines in terms of sedimentation ranges from 74 to 99% for total input and from 47 to 98% for the maximum, instantaneous inputs. The precision of these different values may be improved by linking them to the two major types of natural erosion" [Table 13].*

Table 13. Summary of the main experimental results obtained by Ouvry *et al.* (2012) on attenuation of the flow of suspended solids by hedgerows and fascines *[see Ouvry* et al.*, 2012]*.

		Mean sedimentation rate...	
Grain size of inputs	Erosive process	w/ respect to total inputs	w/ respect to maximum, output concentrations
Group G corresponding to suspended solids of which over 50% of the transported particles are larger than 125 µm in size.	Complete erosion of a volume of soil, no differentiation during pick-up or transport = concentrated flow in a gully or trough.	93 to 99%	89 to 98%
Group F corresponding to suspended solids of which less than 35% of the transported particles are larger than 125 µm in size.	Diffuse erosion during fairly light rainfall.	74 to 91%	47 to 90%

Similar to the results obtained for grass buffer zones, this type of system is less effective for sediment with a higher percentage of fine particles (Group F in this example). Hedgerows would seem to be slightly more effective due to the presence of a herbaceous cover and/or mulch at their foot *[the detailed results of all the experiments are provided in Table 14]*.

Table 14. Summary of the experimental results obtained by Ouvry *et al.* (2012)
on attenuation of the flow of suspended solids by hedgerows and fascines *[see Ouvry* et al.*, 2012]*.

Description				Characteristics of the injected sediment						Hydraulic characteristics					Results					Theoretical transfer (Dabney)
Site	System	dh (cm)	Input	D (mm)	Soil	0 µm to 64 µm	64 µm to 125 µm	125 µm to 2 mm	Group	Q (l/s/m)	n	V* (m/s)	V min. (m/s)	L (m)	Cin (g/L)	Duration (s)	Cout max. (g/L)	Total export	Max. export	Total passage
Albl	Fascine	1	c	< 1	1	38.8	35.7	25.4	F1	2.95	0.42 •	0.057 •	0.037 •	2.8	11	123	2.10	17.0%	22.8%	12.0%
Etle	Hedgerow	7	c	< 1	1B	36.3	32.8	30.8	F1	1.92	0.36	0.044	0.019	2.3	14	136	1.89	9.1%	13.6%	10.4%
Etle	Hedgerow	7	c	< 1	1B	36.3	32.8	30.8	F1	4.10	0.38	0.059	0.031	2.6	27	63	2.80	15.3%	10.3%	19.0%
SGN	Fascine	0	c	< 1	1	33.3	35.1	31.6	F1	2.05	0.50	0.044	0.044	1.8	15	108	2.29	13.1%	15.5%	10.5%
SGN	Fascine	0	c	< 1	1	33.3	35.1	31.6	F1	4.88	0.60	0.055	0.055	2.4	28	72	5.93	21.6%	21.1%	19.0%
TlC	Hedgerow	8	c	< 1	1	39.0	29.6	31.4	F1	3.39	0.32	0.082	0.025	2.5	13	109	2.48	16.6%	35.2%	15.7%
TlC	Hedgerow	8	c	< 1	1	39.0	29.6	31.4	F1	6.51	0.31	0.110	0.047	2.8	15	105	5.01	26.3%	52.4%	26.0%
Albl	Fascine	1	c	< 2	1	69.2	25.6	5.2	F2	2.95	0.31	0.070	0.042	2.8	13	63	2.50	21.1%	23.0%	21.1%
CB	Fascine	0	m	< 2	2	12.5	15.3	72.2	G2	2.62	1.01	0.028	0.028	3.2	13	111	0.41	1.2%	3.4%	2.6%
CB	Fascine	0	m	< 2	2	12.4	14.5	73.1	G2	2.62	1.01	0.028	0.028	3.2	21	111	0.73	1.2%	3.4%	2.7%
Yvc	Hedgerow	6	m	< 2	3	19.4	12.1	68.5	G3	1.93	0.59	0.025	0.016	3.3	9	135	0.89	3.4%	6.6%	2.6%
Yvc	Hedgerow	6	m	< 2	3	19.4	12.1	68.5	G3	3.84	0.57	0.036	0.026	3.8	12	141	1.05	6.6%	2.2%	5.6%
SGN	Fascine	0	c	1 to 2	1	18.7	26.7	54.6	G1	2.01	0.41	0.050	0.050	1.2	19	113	1.39	7.0%	7.5%	9.7%
Albl	Fascine	1	c	1 to 2	1	19.7	26.1	54.1	G1	3.04	0.46 •	0.054 •	0.038 •	2.8	15	99	0.70	3.8%	5.3%	6.1%
Etle	Hedgerow	7	c	1 to 2	1 bis	-	-	-	G1	1.92	0.36	0.044	0.019	2.3	19	109	0.75	2.8%	4.1%	*nd*
TlC	Hedgerow	8	c	1 to 2	1	19.5	26.5	53.9	G1	3.27	0.32 •	0.082 •	0.025 •	2.5	15	93	0.86	4.9%	10.6%	7.6%

dh: difference in elevation between low point upstream and low point of system. A positive value signals a low section just upstream of the hedgerow or fascine.
Input: the supply of water at the end of a sediment pulse is either cut (c) or maintained (m).
D: sieving diameter.
Group: group G: P (> 125 µm) > 50%; group F: P (> 125 µm) < 35%.
n: Manning coefficient.
V*: velocity at foot of the studied system.
V min.: minimum velocity upstream of system.
L: distance between the hydraulic jump and the hedgerow or fascine.
Cin: concentration of sediments at input.
Duration: duration of the sediment pulse.
Cout max.: maximum instantaneous concentration of output.
Total export: total exported mass / total imported mass
Max. export: Cout max. / Cin
0.025 •: data from measurements in clear water, discharges may differ from 10 to 20%.

Annex V ■ Information on sizing a planted buffer zone to limit transfer of plant-protection products

The Corpen guide, published in 2007, already provided data on the effectiveness of grass and ligneous buffer zones (strips) in attenuating the transfer of plant-protection products (drawn from a review of the literature done by Lucas, 2005). It indicated that, in the French context, the experiments run on the buffer zones resulted in reductions *"often greater than 90% and rarely less than 50% for all of the substances studied"* (for widths from 1 to 20 metres). It should be noted, however, that these results are highly dependent on the characteristics of the tested zones and, more generally, on the experimental conditions.

Since 2007, work done by Irstea on limiting pesticide transfers in diffuse runoff using vegetated buffer zones (grass or trees/shrubs) has resulted in a sizing method that is suitable for operational implementation. The method, software and necessary data are presented in detail in the guide drafted by Carluer *et al.* (2011).

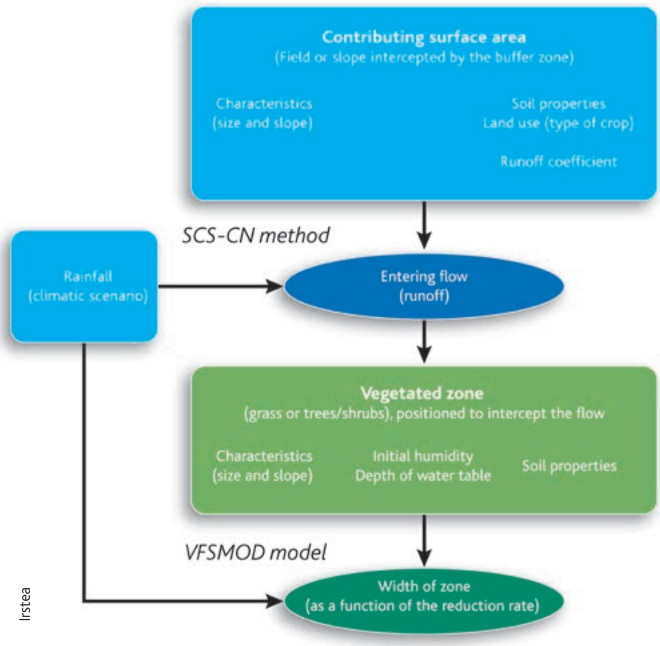


Figure 32. Diagram illustrating the method to size vegetated buffer zones (grass or trees/shrubs) to limit transfer of pesticides in runoff water.

The objective is to determine the width of the buffer zone required to reduce by a given percentage the flow of water (and contaminants) entering the zone via runoff (where a reduction of 100% would correspond to zero runoff exiting the buffer zone). The method proceeds in two steps *[Fig. 32]*:

- quantify the flow of water from the contributing fields upstream of the buffer zone for a rainfall of a given intensity;
- determine the capacity of the zone to absorb (infiltration) the flow.

Each of the two successive steps brings specific tools and data into play. The first step is run using the SCS-CN method *[USDA-SCS, 1972]*, which calculates a runoff coefficient (curve number) that depends on the characteristics of the contributing surface area (soil properties and humidity, size, slope) and the climatic scenarios for the studied area.

The second is based on the VFSMOD (Vegetative Filter Strip Modeling system) digital model, developed in the U.S. *[Muñoz-Carpena and Parson, 2010]*, then validated and adjusted to the French context, notably to take into account water tables at slight depths below the buffer zone, a relatively frequent situation along watercourses *[Munoz-Carpena* et al.*, 2011]*. This model integrates the complexity of hydric transfers, sediment retention and pesticide retention within the buffer zone, on the basis of the zone characteristics (roughness of the cover, soil properties, humidity, slope) and the volume of water entering the zone (datum produced by the previous step). It indicates the width required to achieve the targeted reduction.

It should be noted that the results are adjusted for the type of crop and climatic scenario (part of the input data). Consequently, crop rotations and seasonal variability are not taken directly into account. For this reason, it may be advisable to produce a number of scenarios for a given buffer zone in order to determine the width offering the best compromise for a majority of potential situations, e.g. a width of 10 metres for a 100% reduction in runoff during the summer, but 70% during the winter.

It is also worthwhile to assess different widths as a function of the reduction rate to determine the best compromise between effectiveness, surface area required and cost. The usefulness of a buffer is commonly analysed in terms of the ratio between the width of the zone and the length of the intercepted slope. If the ratio is highly unfavourable, a solution may be to create smaller buffer zones higher up on the slope or within the fields (or to opt for a different type of buffer zone better suited to the particular situation). In this manner, the sizing tool can be used to validate projects or to propose different solutions.

Concerning the positioning of buffer zones, the approach proposed by Dosskey *et al*. (2011) should also be mentioned. The author observes that a buffer zone with a uniform width at the foot of a field is not necessarily the best solution given the variability of the runoff volumes received (locally converging flows may result in most of the water being intercepted by a small part of the buffer). Ideally, the effective width of buffer zones should take this variability into account, in compliance with the recommendations made in 1997 by Corpen *[Fig. 33]* [21].

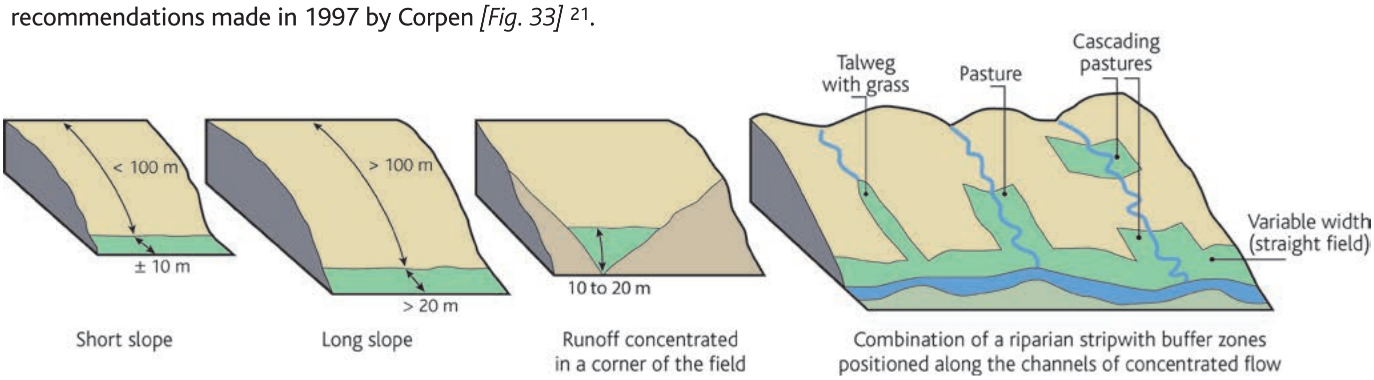


Figure 33. Recommendations made by Corpen concerning the width and shape of vegetated buffer zones designed to attenuate the transfer of plant-protection products via runoff *[see Corpen, 1997]*.

To that end (using an adaptation of the VFS-mod model), it is proposed to quantify effectiveness as a function of the ratio between the surface area devoted to the buffer system and the contributing surface area (in order to make the results comparable). The width of the buffer zone to be set up below the field is then calculated as a function of the drained surface area per unit length (that can be determined using a sufficiently precise digital terrain model (DTM)). This method is useful in that it integrates the concept of a talweg with grass in places where flows converge and minimises the width in areas receiving less runoff. In the end, the total surface area devoted to the buffer system remains unchanged, but its design is optimised to obtain the same degree of effectiveness at all points in the system.

The tools required to use the method developed by Irstea (a set of software utilities) may be obtained free of cost, on request [➔]. However, their effective use is not easy and requires proper training. Study is now being put into developing a new utility to facilitate use of the method.

➔ *http://www.irstea.fr/les-zones-tampons*

To avoid the need to use computer models, Irstea has also developed sizing charts (in the framework of the Topps-Prowadis project, Carluer and Lauvernet, 2014) [22]. The objective is to offer managers with sizing data using a simplified set of parameters representing the various agricultural/pedological/climatic situations. To date, these charts are based on a total of 52 000 simulations summed up in 96 graphs *(see the example in Figure 34)*. For the studied scenarios, the targeted level of effectiveness in reducing runoff was set at 70%.

21. Unfortunately, practically speaking, a buffer zone with a variable width is problematic in terms of the work required in the fields.

22. Note similar, but less extensive work (simulation of seven scenarios) by Dosskey et al. *(2011).*

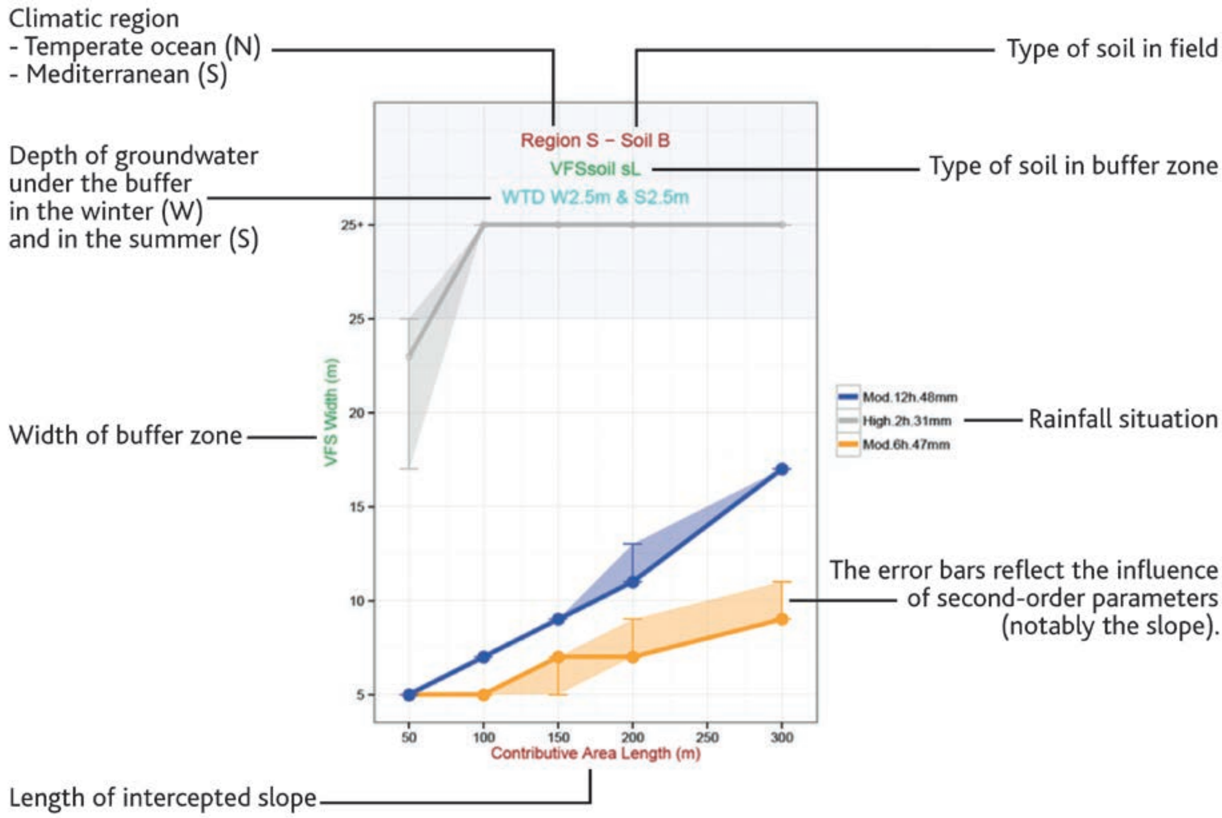


Figure 34. Example of a graph proposed by Irstea to assist in sizing vegetated buffer zones to limit transfer of pesticides in runoff water. Details on the various parameters may be found in Carluer and Lauvernet (2014).

To finish with this topic, it should be noted that the essential factor in the functioning and effectiveness of these systems for dissolved pesticides lies in their capacity to absorb (infiltration) the runoff water. The subsequent fate of the substances below the surface and their possible transfer via sub-surface flows to surface waters or via infiltration to groundwater has been studied very little to date. A number of experiments have shown that the greater part of the infiltrated substances is retained by the soil in the buffer zone during a runoff event or after a few "rinses" *[Boivin* et al.*, 2007]*, however, the possible release of the adsorbed substances and/or of their metabolites over the longer term must still be studied in detail.

Annex VI ■ Information on the effectiveness of water bodies in limiting transfer of plant-protection products and a sizing technique for a constructed wetland buffer zone (CWBZ) starting with a storm basin

From 2006 to 2010, the European Artwet project *(LIFE 06 ENV/F/000133)* studied the means to limit transfers of plant-protection products and bio-phytoremediation in constructed wetlands. It notably involved a series of experiments on different buffer-zone prototypes and resulted in the publication of several guides to provide project managers with practical assistance in creating buffer zones, including economic and social factors to ensure better acceptance [Artwet, 2010a and 2010b]. The main conclusions of the project are reproduced here. A summary of the results obtained on the various study sites is presented in Table 15.

Table 15. Summary of experimental results obtained in the Artwet project to attenuate transfer of plant-protection products using buffer systems (water bodies).

Type of buffer zone		Monitored substances	Effectiveness ((% retention, mass balance)) Mean	Minimum	Maximum
Naturally vegetated storm basin, equipped with a gravel filter *Rouffach site (France)*	Artwet project	Simazine, Pyrimethani, Diuron, Terbuthylazine, Cyprodinil, Isoxaben, Metalaxyl, AMPA, Dimethomorph, Azoxystrobin, Glyphosate, Kresoxim methyl, Terbuthylazin, Gluphosinate, Cymoxanil	82 ± 18%	40%	100%
	Phytoret project	Dithiocarbamates, Difenoconazole, Pyrimethanil, Cyprodinil, Fludioxonil, Metalaxyl, AMPA, Glyphosate, Tetraconazole, Spiroxamine, Cyazofamid, Kresoxim methyl	70%	40%	100%
Constructed wetland buffer zone (CWBZ) downstream of drained fields *Villedomain site (France)*		Isoproturon, Métazachlore, Azoxystrobine, Cyproconazole, Epoxiconazole	73 ± 16%	40%	85%
Holding pond (combined with a vegetated ditch and an "overflow zone") *Landau site (Germany)*		Amitrol, Azoxystrobin, Boscalid, Cyprodinil, Dimethoate, Dimethomorph, Dimetomorp, Diuron, Fludioxonil, Indoxacarb, Iprodion, Myclobutanil, Penconazol, Pyrimethanil, Tebuconazol, Tebufenozid, Thiacloprid, Tolyfluanid, Triadimenol, Trifloxystrobin, Vinclozolin	87%	70%	100%
Constructed wetland, vegetated compartments (highly artificial CWBZ) *Lier site (Norway)**		Dicamba, Dimethoate, Trifloxystrobin, Metamitron, Tebuconazole, CGA321113	90%	65%	100%
Constructed wetland, compartment not vegetated (highly artificial CWBZ) *Lier site (Norway)**		Dicamba, Dimethoate, Trifloxystrobin, Metamitron, Tebuconazole, CGA321113	72%	45%	90%

** The data supplied on this system concerns the peak concentrations.*

"Generally speaking, constructed wetlands reduce exposure to pesticides. In most cases, pesticide retention was greater than 70%. Analysis using multiple linear regression on 188 cases of pesticide retention identified the properties of the pesticides (Koc and DT50 in the aqueous phase), the characteristics of the plant cover and the hydraulic residence time as important factors in achieving maximum retention. A level-1 risk assessment (EU uniform principles) revealed greater reduction in toxicity for highly sorptive and non-persistent insecticides than for less sorptive and less easily degraded herbicides and fungicides. [...]

We conclude that constructed wetlands are an appropriate and effective approach in reducing the risks of nonpoint-source pollution of surface waters by pesticides, it being *noted that further research is required to improve the overall effectiveness of pesticide retention.*

Main results and figures:

- *100% of runoff can enter constructed wetlands, under continuous or periodic flow conditions (except for drainage);*
- *90% of rainfall-runoff events can be handled (Rouffach site);*
- *the reduction in seasonal loads varies from 39% (Simazine) to 100% (Cymoxanil, Gluphosinate, Kresosxim methyl and Terbuthylazine) (Rouffach site);*
- *during the growing season (April to September), mean pesticide reductions of 76 ± 19% (total concentrations) and of 82 ± 18% (estimated total load) can be achieved (calculation based on 52 rainfall-runoff events between April 2006 and September 2010, for 19 pesticides);*
- *a minimum hydraulic retention time of 8 hours is required in a storm basin to reduce by 87% (mean value) the maximum concentrations during runoff, following major storms releasing 30 mm of water (Landau site);*
- *downstream of a drained basin, the reduction is 55% (mean value), with variations ranging from 20 to 90%, depending on the substances (Villedomain site)."*

Following the Artwet project, the Phytoret project (carried out in the upper Rhine region) addressed in more detail certain points concerning the behaviour of plant-protection products in constructed wetlands and rural river basins *[Phytoret, 2014]*. The points below merit particular attention:

- effectiveness levels similar or superior to those obtained in the Artwet project, with predominantly dissolved inputs (95% of the total input load) entering the CWBZ and variable distribution of pesticides (dissolved or suspended solids) depending on the substances *[Fig. 35]*;

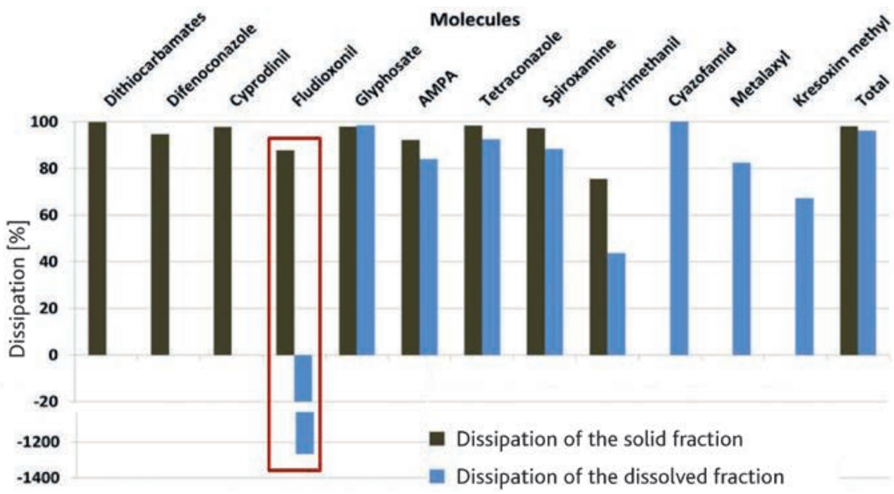


Figure 35. Dissipation (as a percentage of the input mass) per substance and input mode (dissolved and solid fractions) *[see Maillard and Imfeld (2014)]*.

- an in-depth study of dissipation mechanisms for the dissolved and adsorbed phases, differentiating between the degradation (destructive) processes on the one hand and the adsorption and dilution (non-destructive) processes on the other, including study of the potential of pesticide-degradation markers (analysis of enantiomers in the case of chiral pesticides [mirror molecules that are not superimposable] and compound-specific isotopic analysis *[Elsayed et al, 2014a and 2014b]*);

• an in-depth study of the storage, dissipation/transformation and restitution processes revealing a CWBZ "sink" function primarily from spring to summer (with maximum degradation during the summer when the vegetation is mature), but also a "source" function, i.e. the release of certain degradation products. In particular, it was noted that AMPA, a product of glyphosate degradation, accumulates in fine sediment toward the end of summer, which raises questions concerning ecotoxicological risks due to the release of the degradation products in wetlands and the management of sediment in wetlands;

• the hydrological regime and pesticide input loads would not seem to affect the dissipation of pesticides, which varies more depending on the substances and the chemical conditions in the storm basin;

• the development of tracing techniques to understand, at lesser cost, the factors determining the effectiveness of buffer systems;

• the development of two models to assess the risks of exporting pesticides from fields to aquatic ecosystems.

Similar to the Artwet project, the Phytoret project made an effort to disseminate the results to the concerned stakeholders, notably by producing extensive technical documents, by highlighting feedback from various projects and by setting up a database on existing buffer zones in the studied region [→].

→ *https://sites.google.com/a/engees.eu/phytoret/home*

In parallel, work done in the ENRHY project produced several tools (with guides on the methods employed) to optimise the design of retention and remediation systems (RRS) (based on the Rouffach prototype) in order to make best use of the different functions *[Regazzoni* et al.*, 2010]*.

The primary advantage of this type of system is that is uses existing structures (storm basins, flood-control basins, etc.) already incorporated in the hydrosystem, while impacting as little as possible their initial function. It has been proposed to run studies to determine the best compromise between the size required for flood control (degree of protection for a given return period) and the optimum residence time in the system for contaminant degradation. In this case, the decisive element is the output discharge. It must be sufficiently low during common runoff episodes (low intensity rainfall), but not affect system functioning during extreme events. To that end, the proposed solution consists of creating a gravel filter carefully positioned upstream of the output mechanism. Its purpose is to reduce the speed at which the system empties for small water volumes. An initial tool has been developed to study the impact of this type of solution on the degree of protection provided by the system *[Regazzoni and Payraudeau, 2013a]*, based notably on the estimation of the runoff volumes in the contributing catchment and the outflow dynamics of the RRS (before and after the creation of the gravel filter).

When the existing installations are not sufficient for the agricultural surface area in question *[Fig. 36]*, a solution may be to identify the optimum location for a new RRS in the catchment. A second tool was developed precisely for this purpose *[Regazzoni and Payraudeau, 2013b]*. Taking advantage of the functions offered by a geographic information system (GIS), the tool assists project managers in determining the best sites by:

• estimating the flows generated by each point in a landscape for a given rainfall, using the approach employed by the SCS-CN method *[USDA-SCS, 1972]*

• determining the potential sites depending on the storage volume of the RRSs and the rainfall volume of the runoff events that must be intercepted;

• integrating the feasibility (in terms of available land) with the constraints arising from the presence of protected, natural areas in the decision-making process.

This tool can be used right from the initial design phase to study and propose different development scenarios for the river basin. What is more, if the flood-control aspects are disregarded, the tool could easily be adapted to constructed wetland buffer zones intended to intercept hydraulically concentrated runoff.

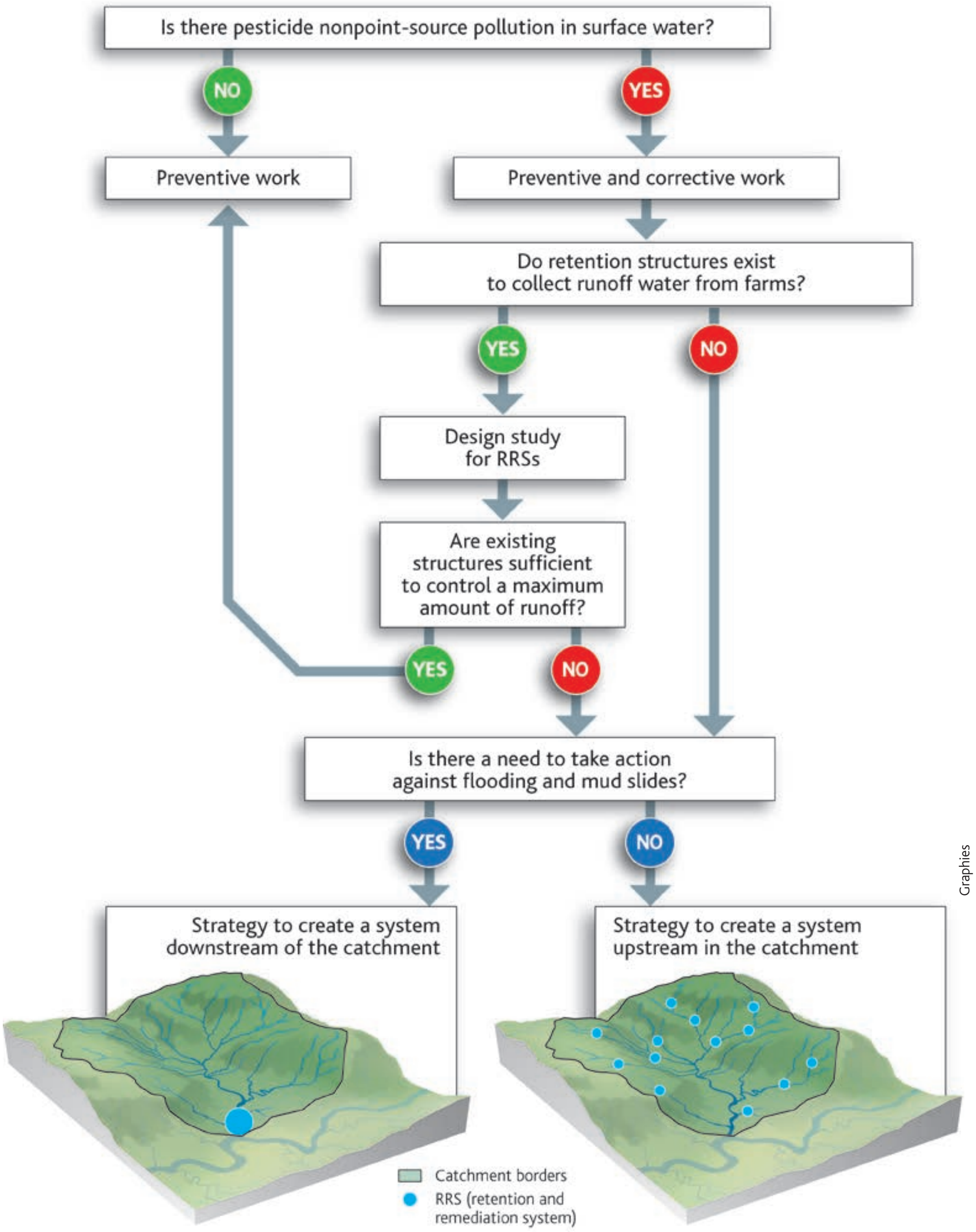


Figure 36. Decision tree used to modify or create a retention and remediation system (RRS) *[see Regazzoni* et al., *2011]*.

Abbreviations

Organisations

- **Areas**: Research group on runoff, soil erosion and management
- **Astee**: Scientific and technical association for water and the environment
- **BZTG**: Buffer-zone technical group
- **Corpen**: Guidelines committee for environmentally friendly agricultural practices
- **CRAL**: Lorraine regional chamber of agriculture
- **IGN**: National geographic and forestry institute
- **INRA**: National institute for agronomic research
- **Irstea**: National institute for research in environmental and agricultural science and technology (formerly Cemagref)
- **Lhyges**: Hydrology and geochemical laboratory in Strasbourg
- **Onema**: National agency for water and aquatic environments
- **UIPP**: Union of plant-protection industries
- **USDA**: United States Department of agriculture

Autres

- **ASZ**: abstraction supply zone
- **CAP**: common agricultural policy
- **CWBZ**: constructed wetland buffer zone
- **DT50**: dissipation time to 50% (half-life)
- **GAEC**: good agro-environmental conditions
- **GIS**: geographic information system
- **Koc**: soil organic carbon-water partitioning coefficient
- **RRS**: retention and remediation system
- **SIAEP**: drinking-water supply board
- **TSS**: total suspended solids
- **ZNT**: pesticide-free zone

Citation: Catalogne C., Le Hénaff G. (editors), 2016. *Guide on setting up buffer zones to limit the transfer of farm contaminants*. Drafted by the Buffer-zone technical group. French biodiversity agency, *Guides and protocols* series, 64 pages.

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Buffer zones are landscape features that can provide numerous environmental functions in rural areas, e.g. avoid runoff and erosion, maintain biodiversity and enhance the landscape. In addition, their capacity to limit the transfer of farm contaminants (pesticides, nutrients) to aquatic environments has been demonstrated and is now acknowledged.

In spite of these positive features, buffer zones are still not widely used in action plans to combat nonpoint-source pollution.

The Buffer-zone technical group, with support from Onema that has in the meantime become the French biodiversity agency, strives to disseminate the available knowledge on the subject and promote buffer zones as a contributing factor to the good practices implemented in the fields themselves.

This guide serves that objective by informing on how to set up a buffer zone and to identify solutions for the various problems involving pollutant transfers in rural areas. It has been designed as a toolbox for people participating in all types of action programmes to protect aquatic environments (protection of abstraction supply zones, restoration of the ecological quality of rivers, etc.).

For more information on Buffer-zone technical group and its work, see:

http://zonestampons.onema.fr/

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* As of 1 January 2017, the Agency for marine protected areas, the Technical workshop for natural areas, the National agency for water and aquatic environments (Onema) and the French national parks joined forces to form the French biodiversity agency.

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