Savoir faire

G. Degoutte, R. Tourment
Editors



# Spillways on River Levees

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Gérard Degoutte and Rémy Tourment
Editors

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# Contents

# Foreword

This handbook was produced at the initiative of the French Ministry in charge of the environment and written by a working group led by INRAE and supervised by the DGPR/SRNH/STEEGBH (General Directorate for Risk Prevention/ Natural and Hydraulic Risks Department/Technical Department for Electrical Energy, Large Dams, and Hydraulics).

The handbook was first published in French in 2012 and initially translated into English the same year, but not published. Gérard Degoutte, Paul Royet (INRAE, retired), and Aline Leclerc (Agora Traductions) worked on the first version of the translation. In 2021, Rémy Tourment (INRAE, chairman of the ICOLD Technical Committee on Levees) updated the English version of the handbook with the help of Adrien Rulliere (INRAE) and translator Diana Huet de Guerville.

The working group in charge of the French version, initially led by Rémy Tourment (INRAE) and then by Gérard Degoutte (CGAAER and INRAE), also included the following members:

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- Gérard Degoutte (CGAAER and INRAE), group leader and general reviewer
- Patrick Deronzier (MEDD/DEEEE), during the first meetings
- François Dols (Director of the Rhône-Méditerranée Water Agency) during the first meetings
- David Goutx (Agro ParisTech then Météo France), co-writer of Chapter 4
- Frédéric Grelot (INRAE), during the first meetings and the review of Chapter 8
- Xavier Martin (CGEDD), during the first meetings and reviewer of an initial version
- Nicolas Monié (MEDDTL/DGPR/SNRH/STEEGBH), co-writer of Chapter 2
- Jean Maurin (DREAL Centre), co-writer of Chapters 3 and 7, writer of Appendix 1, and general reviewer
- Paul Royet (INRAE), main writer of Chapter 6 and general reviewer
- Rémy Tourment, group leader, general reviewer, and coordinator of the second English version
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- Yves Le Trionnaire (MEDD/DE), during the first meetings
- Thibaut Mallet (Symadrem), co-writer of Chapters 4 and 7

The following people also helped write the French version of this handbook:

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# Introduction

The likelihood that overflow will occur on flood protection levees is far from insignificant. When water overflows an earthen levee, it greatly increases in velocity and erodes the levee slope or toe. This erosion extends backwards and opens up a breach that provokes sudden flooding in the supposedly protected area, often with significant economic impact. The suddenness of this process can lead to human casualties in areas with inhabitants or transport infrastructure.

Levees are a double-edged sword: they offer protection against medium-sized floods if properly built, but can create a hazard during high floods if no provisions are made to secure them against overtopping.

Dams almost all have flood spillways to prevent even extremely rare floods from overflowing over their crests. **Can we systematically apply this technique to levees, particularly earthen ones?**

This technical handbook outlines the benefits and limitations of spillways on flood protection levees. Some spillways can protect leveed areas by limiting the adverse consequences of overflows. They are meant to be used infrequently. Other spillways are specifically designed for flood control and are used on a more regular basis. Since these two types of spillways have very different objectives, we will refer to the former as safety spillways and the latter as diversion spillways. Some structures, especially the oldest, actually play both roles. The hydraulics remain the same regardless, and this handbook covers all types of levee spillways.

**What types of levees?** This handbook examines flood protection levees on rivers, including mountain torrents. We will not address levees along coasts or canals. We focus on existing levees that already have spillways or the possibility of adding them, as well as new levee projects that could incorporate spillways into their construction design.

# 1

# Background, definitions, various configurations

Gérard Degoutte

This chapter provides an overview of river levees, levee systems, and their potential spillways. We will first describe the various configurations before addressing their purpose. A spillway's function is closely tied to the purpose of the area it protects or fills with water, with a broad range of scenarios we will examine in closer detail.

## Typology of flood protection levees on rivers

### Definition

Levees are typically very long structures built above the natural ground level to either channel water or prevent it from flowing through. Excluding those built along canals, levees are designed to protect certain areas against river or marine flooding. This handbook only addresses riverine flood protection levees that provide partial or total protection against floodplain inundation.

As we will see later, levees may protect against certain floods while only delaying stronger ones. But this is a consequence of the definition rather than part of the definition. The main issue is that the presence of a river levee is a double-edged sword: it offers protection against small- or medium-sized floods but creates a hazard during strong or extreme floods or when it is poorly maintained. If the levee fails, the resulting flood wave may cause even more damage in the floodplain than if there had been no levee at all. Earthen levees offer particularly low resistance to overflows. They may also breach before overflowing because of internal erosion, toe scour, or sliding.

These levees (sometimes called "dry levees") are seldom subject to hydraulic loading, much like flood retention dams or basins.

River levees are generally made from earthfill taken from the riverbed or the surrounding area. They are sometimes built of masonry or concrete, particularly on urban sites, in which case they are sometimes called dikes.

Earthen dams are also sometimes called levees, but this term is incorrect and should be avoided. A dam is built across a river to block at least the riverbed, and frequently the floodplain and beyond. A levee, on the other hand, never blocks the riverbed.

Levees may connect several natural topographical features such as hillsides, promontories, or terraces. Although these natural features are not considered levees, we should analyse their resistance in the same way as human-made levees. We must clearly define the area that is being protected from flooding by one or more levees and potentially some natural features. All these components taken together form what we call a leveed system.

## Longitudinal levees

In leveed valleys, the goal has often been to prevent water from entering most of the floodplain. The levee runs parallel to the watercourse, either at the riverbank level or some distance away. In the latter case, the space between the levee and the riverbank is called an unprotected floodplain or *ségonnal* in French (Figure 1.1). As its name suggests, this area is not protected by the levee and will be inundated by even higher water levels if flooding occurs.

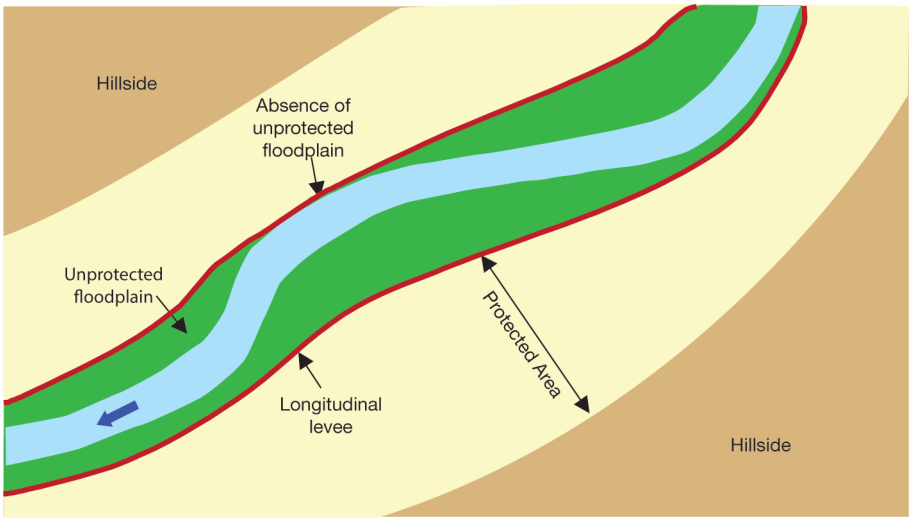


**Figure 1.1.** Longitudinal levee and unprotected floodplain.

## Close protection levees

Levees that prevent large areas from being submerged will worsen overtopping downstream and on the opposite bank. This is why close protection levees are built as near as possible to the stakes to be protected, thereby expanding the flooded area (Figure 1.2). If the stakes to be protected are next to the hillside, the close protection levee will close onto it. If all the stakes to be protected are in a flood-prone area, the close protection levee may be called a ring levee.

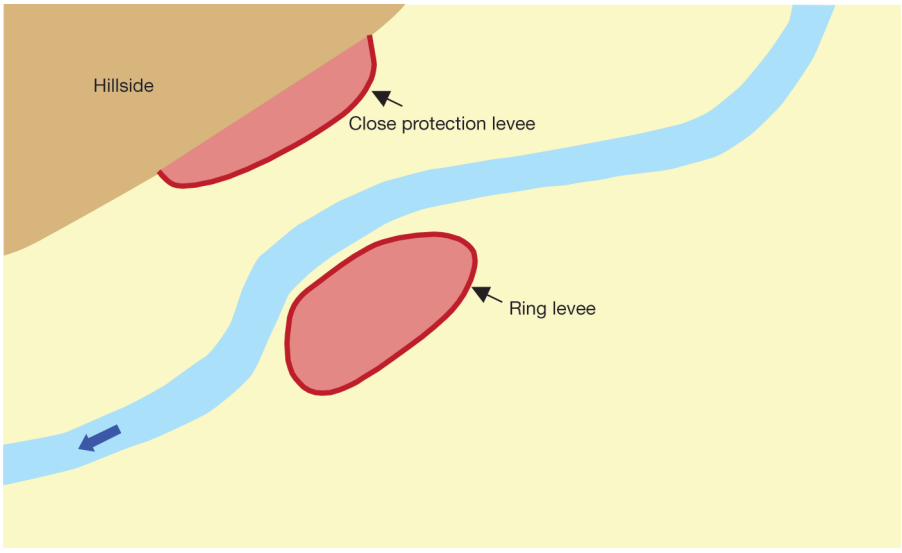


**Figure 1.2.** Close protection levees completely or partially surround areas to be protected.

## Levee rank

A close protection levee may complement a longitudinal levee: a primary levee protects mainly rural areas and a secondary close protection levee protects mainly urban areas. The rank of protection refers to the order in which levees go into effect in the event of a strong flood. No other consideration, either in terms of volume or height should be inferred. In Figure 1.3, on the right bank, the "secondary levee" designation is clear. The area on the left bank is protected from overflows by the longitudinal levee. A peripheral levee prevents discharge into the floodplain from a tributary, a spillway, or an upstream breach. In this configuration, it is hard to say which levee will be activated before the other, so no particular rank of protection is given.

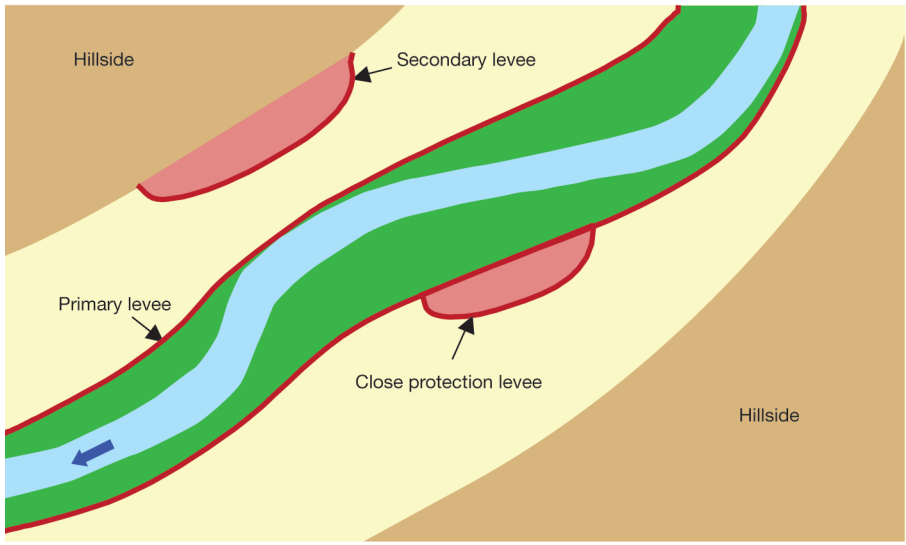


**Figure 1.3.** Primary and secondary levees where applicable.

### Transverse levees

Transverse levees are built perpendicular to the general direction of the valley. They complement longitudinal levees and protect against upstream or downstream inflows. In Figure 1.4, on the left bank, two transverse levees close onto the hillside and isolate a protected area. The upstream levee prevents water from flowing into the flood plain and the downstream levee prevents water from flowing from downstream due to the backwater effect. On the right bank, the transverse levee does not enclose a protected area but splits it into two parts. This may help protect the downstream section if there is a breach upstream. This type of levee may also separate two leveed areas with different purposes: a flood expansion area upstream and a flood protection area downstream. One example is the La Montagnette levee between Vallabrègues and Tarascon, shown in Figure 1.14, or the canal levee between Tours and Saint-Pierre-des-Corps.

## Protected areas and flood expansion areas

We define two types of leveed areas in very different contexts: protected areas in urban environments and flood expansion areas that are preferably non-urbanised. As we will see later, an area can be either a protected area (up to a certain water level) or a flood expansion area (above this level). We use the term "leveed system" to mean either of these. A leveed system is an entire area in a floodplain that has some level of flood protection thanks to one or more levees or natural topography (such as the valley slope).

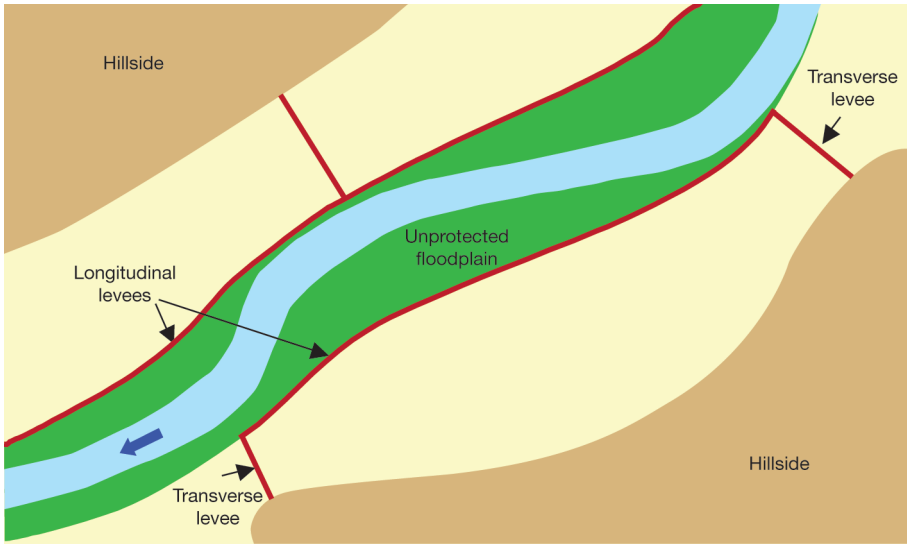


**Figure 1.4.** Transverse levees.

## Protected area

The term "protected area" is quite standard in France. It was used in French Decree 2007-1735 of 11 December 2007 on the safety of hydraulic works, without being properly defined. The *Environnement* circular of 8 July 2008 on this decree includes the following definition:

"A protected area is the area that will not be inundated by a flood that reaches the structure's protection level. It is not the more limited area in which residents would be endangered by high or fast water levels in the event of a levee failure. Neither is it an area that is inundated for the design flood level in the PPRI (Flooding Risk Prevention Plan) by known high water levels, a 100-year flood, or the maximum floodable area."

The more recent French Decree 2015-526 of 12 May 2015 also mentions protected areas; a protected area is associated with a levee system and a protection level. A protected area can also include specific parts associated with different protection levels.

A protected area is a contiguous surface that is protected from flooding by a set of levees or other structures (road embankments, etc.) or a raised topographical feature such as a hillside or a terrace. It is an area that is likely to flood without a levee and is protected from flooding as long as the levee plays its protective role – that is until the levee is overtopped or damaged. See Figure 1.5. For close protection levees, as shown in Figures 1.2 and 1.3, the protected area is clearly defined.

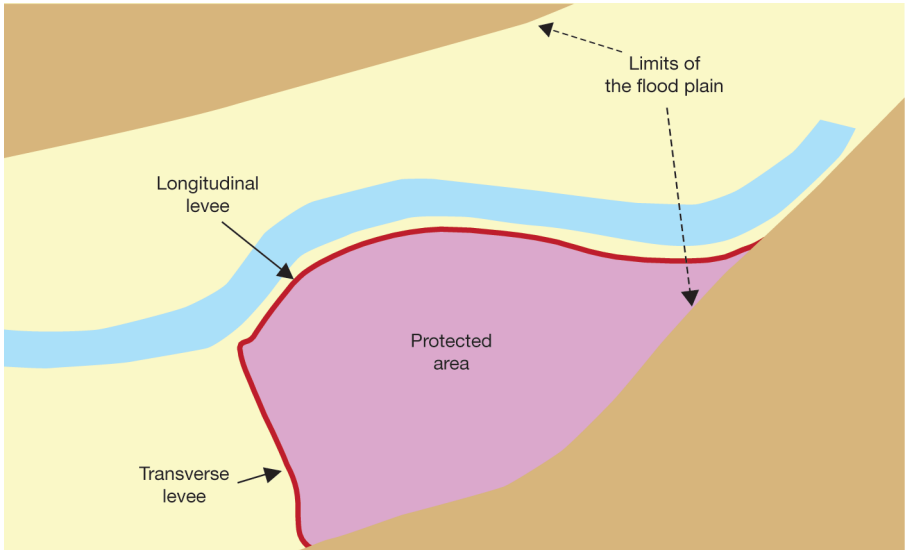


**Figure 1.5.** Area protected by a longitudinal levee, a hillside, and a transverse levee. This configuration will be effective whatever the direction of the river current.

In Figure 1.5, the protected area is closed and must include a drainage system.

Another option is for the protected area to be partially open downstream. See the example in Figure 1.6. This area is closed by the levee on one side and cut off by a tributary flowing on the other side through the hillside. This will allow common floods to fill in the area from downstream through the backwater effect. The entire area is not a protected area since a small section at the junction is flood-prone, while the rest is protected by the levee.

Most of the protected areas that have been built recently or are currently planned are in highly urbanised areas. After all, there is no need to protect an area in which flooding will have limited impact, or in which there are no stakes. In the past, however, mainly rural areas were protected. Camargue Island is probably the best example, along with the Isère River Valley upstream from Grenoble, the Save River Valley in Gers, the Vidourle River Valley, and many more.

## Flood expansion area

Our definition of a flood expansion area comes from the French water portal (www.eaufrance.fr) and French Master Plan for Water Development and Management: "A flood expansion area is a natural or leveed area into which water spreads when a watercourse overflows into the floodplain. Temporary water storage attenuates the flood by extending its flow time. This storage helps aquatic and land ecosystems function properly. A flood expansion area typically refers to areas with no or limited urbanisation and development."

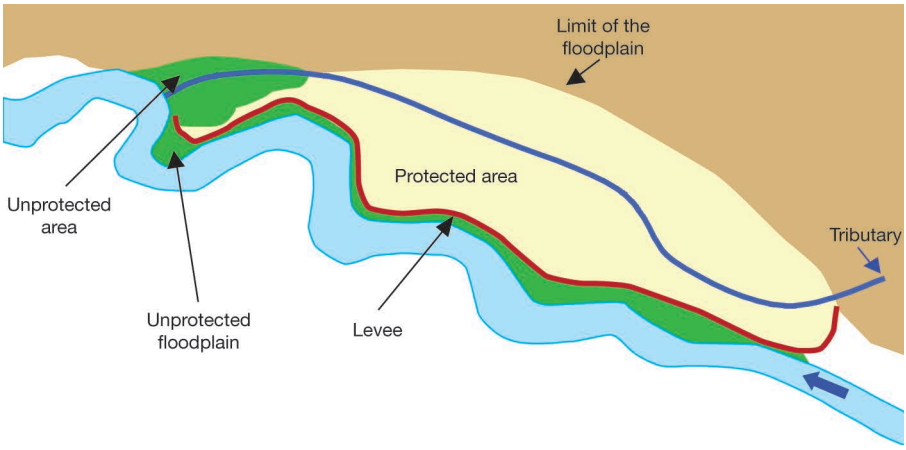


**Figure 1.6.** Open protected area: a downstream tributary flows through the levee.

Even though it is not the focus of this handbook, this definition shows that natural (therefore non-leveed) riverine floodplains are flood expansion areas. They are not constrained by structures such as levees. The construction of longitudinal levees is designed to limit flood expansion, at least for all floods that cannot flow over the levee crest or destroy it. Efforts to add levees or backfill to the floodplain limit the expansion areas and increase peak discharge downstream, requiring more and more construction features.

This is why priority should be given to flood retention structures or measures. In this context, the areas designed to be flooded are also flood expansion areas. To differentiate between these two cases, we will use the terms natural vs. controlled flood expansion areas to avoid any confusion. Other acceptable, though more infrequent terms are also used for controlled flood expansion areas such as controlled flood fields in the Isère River Valley and dynamic flood retention areas.[1]

Natural and controlled flood expansion areas can both contribute to a dynamic flood retention strategy, as do other structures such as flood attenuating dams, diversion basins, setting back or removing levees, floodplain forestation, installing hedges perpendicular to the direction of the flow in the floodplain or catchment area, and any other changes to the area. In the rest of the handbook, we will use the term (natural or controlled) flood expansion area rather than dynamic retention for accuracy, even though flood expansion areas do perform dynamic retention.

Flood expansion may have a hydraulic or ecological function or both. The goal is to reduce downstream flooding through temporary water storage. This also preserves the ecological value and diversity of the floodplain.

1. For more information on dynamic retention, see the publication by the French Environment Ministry (Chastan et al., 2004).

A flood expansion area is based on natural contours but may also use artificial embankments (Figure 1.7). Water flows in naturally when the river is not leveed. If the river is leveed, water flows artificially over a weir on the levee. Less frequently, water may also be pumped or siphoned in (in this case, a spillway is not required).

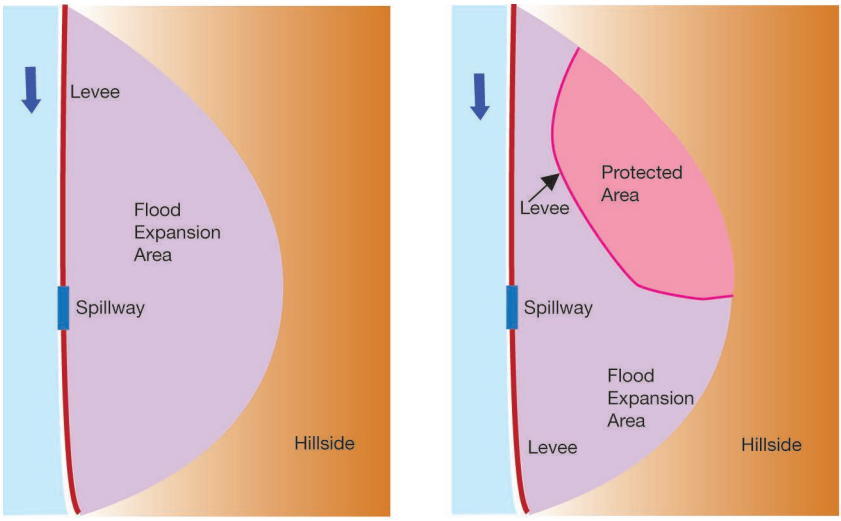


**Figure 1.7.** Controlled flood expansion area fully enclosed by natural flood expansion features on the left; limited by a protected area on the right.

Figure 1.14 below shows an example from the Vallabrègues flood expansion area on the Rhône River.

In a flood expansion area based on natural features, no overflow occurs compared to an area without a levee or spillway (Figure 1.7, left). However, in a flood expansion area whose floodable footprint has been strongly reduced by borrow materials or levees, overflows might occur (Figure 1.7, right).

Controlled flood expansion areas are generally non-urbanised (or only slightly urbanised). They can be agricultural, forest, or ecological areas where some sports or leisure activities may also be possible.

Maintained or reactivated flood expansion areas help temper downstream floods (making them weaker and more spread out). The weaker the downstream flow, the lower the waterline. When the flow is subcritical, waterlines are also lower over a certain distance upstream, via the backwater effect. We will return to these hydraulic aspects in Chapter 3.

A controlled flood expansion area is also a protected area. As long as the spillway does not overflow into the flood expansion area, this area is protected by the levee. Of course, a natural flood expansion area is not a protected area (since flooding occurs there).

## Characteristics of flood expansion areas within protected areas

Here we are only referring to controlled flood expansion areas, meaning those with levees. These are also protected areas, but with a specific purpose.

For now, we will ignore what these areas are called and focus on the developer's goal, such as optimal flood attenuation. Developers may want the area to be flooded relatively early, as long as there are limited stakes. If necessary, isolated residential areas can be offered close protection. This is typical in a leveed flood expansion area (which is also a protected area).

Developers may want to protect a densely populated part of the flood expansion area, using a close protection levee to minimise the reduction of the natural flooding area and limit both upstream and downstream impacts. This is typical of a protected area in the strictest sense. Protection should be as close as possible to the stakes. The purpose is not to attenuate floods, even though a slight attenuation could be useful.

Developers may also have a dual purpose: flood attenuation and protection of an area with important stakes. This is surely what inspired the Comoy levee project two centuries ago (see Appendix 2, "A history of spillways on the Loire River"). Before that, most of the Loire Valley was composed of protected areas with extensive rural spaces. Flood attenuation was not the objective, on the contrary, since at the time it was thought that levees could be non-submersible. This is why some large protected areas do not have close protection levees. For instance, the Authion leveed area extends over 200 $km^2$ and now protects 50,000 inhabitants. It does not have a spillway. The leveed areas in which Comoy spillways were built are still protected areas, but their impact on flood attenuation is significant, especially through cumulative effects. They can therefore be considered protected areas as well as flood expansion areas. This is the case of the Ouzouer leveed area, with 5,000 inhabitants in 65 $km^2$.

It is important to remember that the objectives were very different in the first two cases (optimal flood attenuation and protection of a densely populated area). In a protected area with high stakes, any inflow of water should be avoided, whether from the river overflowing, levee overtopping, or levee failure. Most often, spillways in these areas only start operating above a 100-year flood level. Conversely, in controlled flood expansion areas, overflows are encouraged at the ideal time to ensure suitable flood attenuation. Typically, flood expansion areas are flooded for 10- to 50-year floods, meaning far more frequently than in protected areas.

Despite their differing purposes, these areas are all similar in terms of overflow. They follow the same hydraulic rules:

– A controlled flood expansion area first serves as a protected area for moderate floods that do not reach the spillway crest.

– It then becomes a flood expansion area and helps protect downstream areas; a flood expansion area is designed to protect both downstream areas and its own territory.

– Once a high-stakes protected area is flooded by the spillway, it necessarily becomes a flood expansion area; if it covers a large surface, it can help attenuate flooding. This is also the case for a protected area without a spillway if there is a breach in the levee.
– Lastly, some areas may be considered both flood expansion areas and protected areas, such as the Loire leveed areas mentioned above. The Camargue is currently a protected area, but it could also be used for flood expansion in the future.

However, these areas are very different in terms of spatial planning. A protected area without a flood attenuation objective is most likely urbanised, whereas a flood expansion area is generally non-urbanised.

Making a case-by-case distinction seems critical for spillway design. In Chapter 3, we will look separately at the design of diversion spillways in flood expansion areas and safety spillways in protected areas. When an area is both a protected area and a flood expansion area, designers face additional constraints since it is impossible to optimise both protection and flood attenuation.

Of course, nothing prevents us from reasoning at the watershed level:
– A flood expansion area on its own is not that beneficial. Only an entire set of natural or controlled flood expansion areas will have a significant impact on flooding.
– A protected area is a unit of protection that can be effective on its own, but a set of protected areas could have a negative impact by reducing the floodable area too strongly.

### In summary

The floodplain of a leveed valley may include:
- Protected areas designed to reduce flooding frequency and, if possible, protect the area against rare events that may cause overflows. To keep from reducing the floodable area too sharply, the protected area should not extend too far – meaning the protection should be placed close to the stakes.
- Natural flood expansion areas, where flooding is permitted, to prevent any increase in downstream flood flows; we will not cover this topic.
- Controlled flood expansion areas where flooding is facilitated to reduce flood discharge downstream and/or for ecological purposes.
- Protected areas where flood attenuation is also intended, and which may be referred to as a protected area or flood expansion area, depending on the topic.

This handbook is primarily focused on spillways in protected areas in the strictest sense, as well as spillways in controlled flood expansion areas.

## The fragility of levee systems

Earthen levees may experience damage from a variety of causes, mainly internal erosion, external erosion in the case of overflows, scour with levees at riverbank level, or collapse of the slope. These mechanisms can lead directly to a breach, or create a chain reaction in the form of processes (scenarios) that can also lead to a