

Levees, Diversion Canals or Flood Expansion Areas?

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Abstract. Risk Flood protection involves works which reduce the hydraulic hazard in protected areas in terms of frequency, duration, water level, water velocity or flood arrival time. These works are parts of protection systems. In this paper, we discuss and compare three structure-based solutions that contribute to flood protection but seem to oppose one another in the mind of general opinion: levees based protection systems, whose purpose is to prevent water from spreading in protected areas; diversion channels that aim to decrease the flow at their downstream; flood expansion areas, whose purpose is to temporarily store water, reduce flood peak and spread flow duration. The article also deals with weirs which can be found in addition to dikes in the three types of solutions on which the paper focuses. For each type of these flood protection solutions, the paper describes their functions and limits, details how these solutions are similar, opposite or complementary, and in the end shows that they are globally complementary and not mutually exclusive. It also demonstrates the interest of a multi-scale analysis and of an integrated design and management of these arrangements, taking into account flood risk, morphological changes and associated environmental objectives.

1 Introduction

Amongst the various measures and tools contributing to flood prevention, protection (sometimes also called defence) is the best known, the most visible, and therefore the one which is most likely to be requested by populations and local stakeholders. Protection calls for structures which function is to reduce, in the areas they protect, hydraulic hazards in terms of:

- frequency;
- duration;
- water velocity;
- water level;
- or of the moment when flooding occurs.

These structures can be levees, grouped together or complementing other structures or natural elements in protection systems, or dams, canals, or dynamic retention structures.

It is unrealistic to think that protective structures alone will be enough to prevent flooding risk (all structures have their own limitations, and the possibility of failure before their limit too), and even more so to think that they would be sufficient as stand-alone solutions. Other measures need to complement the purely hydraulic effects of flood protection structures reducing the natural hazard by playing on non-material aspects in order to scale down

the consequences of flooding [9]. French natural risk prevention policy rests on seven complementary cornerstones¹:

- knowledge of hazards and stakes;
- monitoring, forecasting, vigilance and warnings of events;
- education and preventive information campaigns aimed at citizens;
- implementing regulations to control land development and adapt constructions;
- reducing vulnerability;
- protection structures;
- developing a preparedness to critical or emergency situations.

This preventive approach is similar to the "multiple layers of safety" concept developed in the Netherlands, which comprises three safety layers to reduce flood risk: flood protection, spatial planning, and emergency response [10], which was introduced by the 2009-2015 national water plan [15].

Nowadays, the challenge is rather the management of flood risk (through analyzing, evaluating, and reducing it), rather than its total elimination.

¹ www.developpement-durable.gouv.fr/Introduction,24018.html

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This paper will discuss and compare three solutions based on structures which contribute to flood protection and are perceived as antagonistic in the public mind: flood protection systems based on levees, diversion canals, and flood expansion areas. We will describe the functions and limitations of these solutions, examining how they are comparable, opposed, or complementary. Flood-control, also called flood retention dams are also structures that are intended to limit floods downstream, but we will not examine them specifically in detail. On the one hand, the biggest ones have a broad effect in terms of downstream influence, on the other, they are already perceived as being a compatible, rather than as an alternative to the structures mentioned above.

Flood prevention and protection via structures concern a range of type of sectors: sea, river, torrent, or mixed influence sectors (estuary, torrential rivers...). Based on their principle, diversion canals and flood expansion areas only pertain to inland water bodies, whereas embankment systems are worth considering both for protection against flooding from both inland and maritime origins. This paper will therefore only address inland water, except in specific cases.

2 Flood protection systems components

2.1 Embankments: dams or levees

In everyday language, embankments broadly relate to embankment works used for containing water. In the specialized terminology of hydraulics works, there is a distinction between embankment dams and levees depending on their effect on water. Dams retain water upstream, whereas flood protection dikes, also called levees, on the contrary, prevent water from spreading into unprotected areas (Fig. 1). Furthermore, levees or flood protection dikes are to be distinguished from canal embankments (for both waterways or aqueducts) or breakwaters (in harbors, or along coastline for erosion control); only the former are of concern to us in this paper. It is therefore clear that the three planning solutions addressed in this study will include levees: levee systems, naturally, diversion channels, so long as they are not entirely dug structures and many flood expansion areas.

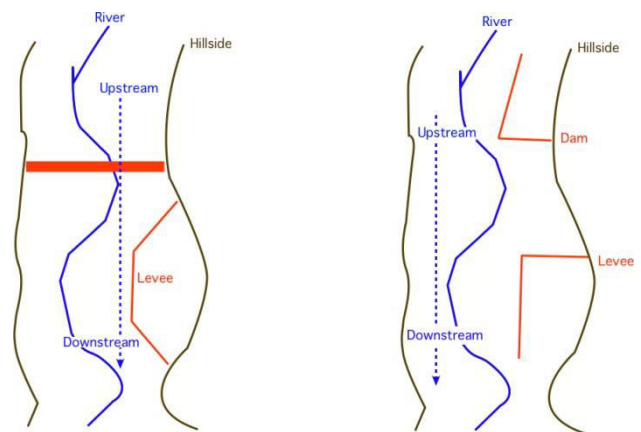


Figure 1. Distinction between dams and levees (diagrams by Rémy Tourment, IRSTEA). The left-hand diagram represents a dam which blocks an entire valley and a closed levee system. The right-hand diagram presents open systems involving dikes, the top one working like a dam, and the bottom one like a levee. Distinction of the function is not always easy on open systems.

2.2 Spillways

Spillways are found on almost any dam, but also on levee systems [5]. A spillway built on a levee is, like any levee section, another component of a hydraulic structure. The roles of a spillway are: to support the passage of water from one side to the other without causing damage, to hydraulically control this passage in terms of relation between water level and discharge, and to avoid damage on the rest of the levee system, which does not resist to overflowing. Spillways are usually found on the three types of structures that will be examined: levee based flood protection systems, but also in relation to with levees in diversion channels and flood expansion areas.

3 Levee based flood protection systems

Flood protection systems, or levee systems, obviously feature levees, with sometimes spillways, but often, they also feature other natural elements (dunes, hillocks, hillsides, rocky headlands...) or artificial ones (transport or other infrastructure embankments, or even buildings). All of these high ground elements that rise above a plain actually protect it from flooding (Fig. 2), and not only the specifically built levees.

An international handbook [2] and a technical reference guide commissioned by the French Ministry of Environment's General Directorate of Risk Prevention [7] now clearly introduces the principles involved in these protection structures and systems, both in terms of their design and of their management.

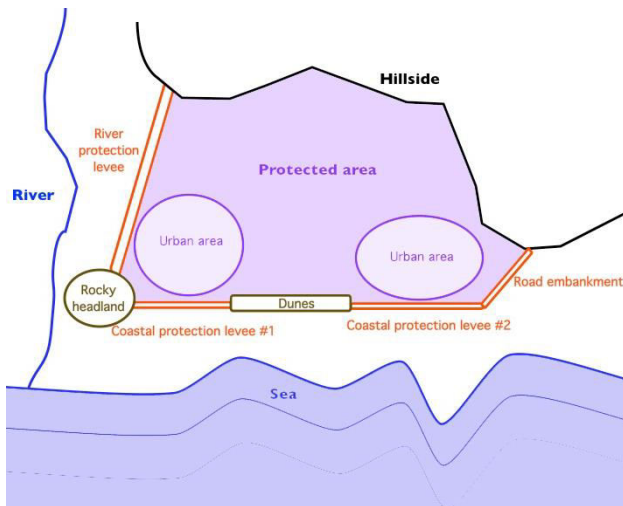


Figure 2. River and sea flood protection system (diagram by Rémy Tourment, IRSTEA).

Embankment systems limit flooding in protected areas and avoid flooding up to a "protection level." In general, they lessen the hydraulic hazard across the protected area in terms of the water's frequency, duration, speed, of the level it reaches, or of the moment when flooding occurs. In well-known systems, a flood's onset, as well as its characteristics once it starts, are controlled, allowing for relevant management of residual risk. Such is the case for overflow-resilient systems, which have spillways or sections able to resist overflowing, thereby controlling and reducing residual flooding characteristics (beyond the protection level) in terms of water levels, velocity, surges, and flood duration. Sections that are resistant to overflowing contain levee surfaces (at least on the crest and on the protected side slope and beyond) with a revetment able to resist external erosion. Lighter techniques that are less costly than regular concrete spillways allow for overflowing on a longer linear structure, with a lesser overflowing head. This technique can provide a better response than a more classical spillway, which concentrates flows into protected areas, and will thus be more likely to be accepted by residents [3]. Protection against torrential rivers and even more so against torrents most often integrates protection against erosion and the shifting of the water bed in addition to strict flood protection. Torrential protection systems can be quite different to river or sea protection systems.

All levee and more generally flood protection systems have their limits. Floods will occur beyond the protection limit of any system, with annual probabilities usually ranging from 0.2 or 0.1 for agriculture land up to 0.01 or 0.005 for the best protected populated areas, with an exception in the Netherlands where this limit can go up to 10^{-5} . The residual floods may be controlled via overflowing onto a spillway or by a backwater effect on parts of the system without levees, for example in downstream areas, usually at junctions. Some levee systems can also have uncontrolled floods after the protection limit, when overflowing occurs on a non-resistant section of the system, leading nearly

systematically to breaches, which would, of course, not be advisable.

This protection limit therefore corresponds to a variable altimeter level in the flood protection system (Fig. 3). It can also be associated to a historic or modelled event, for instance a 100-year return period ($P_f = 10^{-2}$) predetermined flood.

Another limit also relates to the intrinsic safety of a system's structures. It would be preferable for a levee not to break down before reaching the protection's limit (first overflow), but this is not necessarily the case on older existing systems that are poorly known and have not been maintained for decades and even centuries.

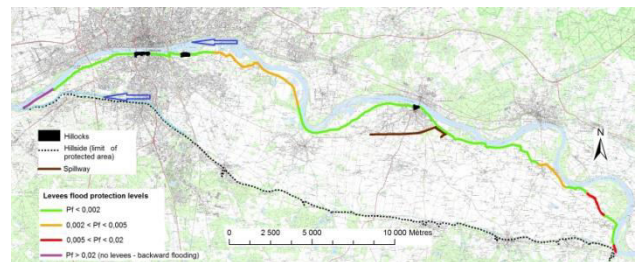


Figure 3. Val d'Orléans protection system and its overflow levels: IRSTEA, adapted from the study on Dangers in the Val d'Orléans, DREAL Centre).

Protections with levee systems have several drawbacks in terms of risk management, as demonstrated recent flooding events in France that involved levees: Camargue delta in 1993-94, the department of Aude in 1999, the Rhone River and its tributaries in 2002 and 2003, Xynthia storm in 2010, to only quote the most devastating events. The decreased frequency of flooding in the protected areas contributes to the populations and even local authorities losing sight of the fact that these areas are naturally liable and still liable to flooding, even with the levees, which leads to increased vulnerability as well as to less reliable responsiveness.

In terms of risk knowledge, uncertainties on how levees will perform before a thorough diagnostic is carried out present many drawbacks. Flooding caused by a breach in a protected area can occur at an unplanned location or time (before overflowing has even occurred); it can occur with incredible force, which would prevent the implementation of appropriate safeguard measures. Furthermore, from a purely physical point of view, levees accelerate downstream water flowing in the river (shortened inflow times with an increased maximum flow), as well as nearby watercourse speeds (which have an effect on erosion, and therefore on potential breach failures on the levees themselves).

In order to be flexible in the event that water should reach above the protection level, and to avoid breaches caused by overflow erosion, river flood protection systems should include an overflow management system, for example one or several safety spillways ([5], p. 23). Generally, these spillways need to be integrated into the embankment system, but they may also be located nearby, on neighboring systems, as long as the drop in the

watercourse's level is enough to prevent any overflowing into the initial system.

In the Val d'Orléans (see the map in Figure 3 presenting the protected area and the protection and overflow levels), morphological evolution has occurred since the system was built, at the end of the 19th century. Therefore, nowadays, overflows can occur on levee segments that were not intended as such, before the Jargeau spillway actually begins to discharge. The recent risk analysis (Etude de dangers) conducted on this system, which has brought these protection and overflowing limits to the attention of the authorities, as well as the limits in terms of levee safety levels, now serves as the basis for considerations on how to mitigate these failings.

In the case of sea protection, the effect of lowering the head is illusory, though many structures nonetheless are wholly resistant to overflowing and overtopping. For example, in Saint-Jean-de-Luz, the entire levee which protects the center of town against the sea flooding, locally known as the "protection weir" (Photo 1), is built like a typical spillway, both in terms of its shape and materials used, and therefore makes it possible to resist overflows and the passing of the sea.



Photo 1. The "protection weir" in Saint-Jean-de-Luz (photo by Rémy Tourment)

4 Diversion Canals

The purpose of a diversion canal is to lower a watercourse's downstream water level. Such a canal is most often water supplied by a spillway on levees located along a main watercourse. Generally, these canals must make up for a watercourse's insufficient local conveyance, and join together further downstream; for example: the Coursan diversion canal (Department of Aude, France) (Fig 4), the Bouillie overflow duct in Blois (Department of Loir-et-Cher, France [4], [5]).

The hydraulic function limit of a diversion canal is its section, which will impose the maximum flow that can be diverted. Although it is possible to consider diverting flows corresponding to frequent floods, it is not advisable to consider diverting rare or exceptional floods unless considerable works can be undertaken for instance divert water up to the sea. When joining the watercourse

downstream isn't possible, for example as a way of protecting other assets, another outlet needs to be found, such as a lagoon, a lake, the sea, or another watercourse. Such is the case for the Lez diversion canal in Lattes (Department of Hérault, France), which flows into the Méjean lagoon ([5], p. 28). This outlet imposes its own limits to water levels in the canal, from downstream, as it may be temporarily elevated by an exterior factor (its own flooding, abnormally exceeding high tide levels...).

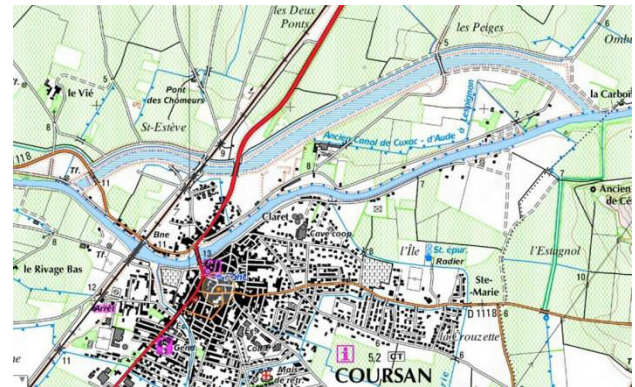


Figure 4. Coursan diversion canal, to the north of the Aude river (source: IGN geoportal).

Arles is located close to a narrowing of the river bed on the Grand-Rhône river, which considerably increases upstream flow lines including on the Rhône; it is not possible to broaden the river bed, because of urban land use. Rhône Plan, that was validated in 2006, poses the principle of protecting the most densely populated neighbourhoods, mainly in Arles, and to adjust the protection level between Tarascon and Arles, according to the flow capable of transiting through the Arles narrow river bed. To provide full protection against a 10^{-3} yearly probability flood in the urban neighbourhoods of Arles, the Plan has defined a lower level of protection (though it is above the 10^{-2} yearly probability flood) in neighbourhoods which have less at stake [8]. The municipality of Tarascon considered that protection offered in the Trébon area, which stretches on the left bank between Arles and Tarascon, is insufficient. It has therefore decided to study a solution that is complementary to the Rhône Plan, the Arles bypass canal (Fig. 5). The canal would offload the Petit Rhône towards the Grand Rhône. Its explicit objective is to lower the flow line in Arles, but also in the Rhône in order to reduce, or even to eliminate the need to plan for water flooding by spillways upstream of Arles, thereby reducing the occurrence of flooding in the Trébon plain. In 2008, SYMADREM (*Syndicat mixte interrégional d'aménagement des digues du Delta du Rhône et de la mer*), which is the main Rhône Plan works operator, commissioned a simulation of the consequences of the project.

A first scenario, which doesn't include mobile works, does not sufficiently address the objective for lowering the flow line downstream from Arles to exclude any discharge before the reference flood. It therefore highlights the confirmation for the need to add a reliable levee along the Arles-Tarascon railroad track. It would

have more negative consequences on sedimentation in the Petit Rhône. Finally, it would have unfavourable effects on the overflow onto the Grand Rhône, downstream from the canal outlet.

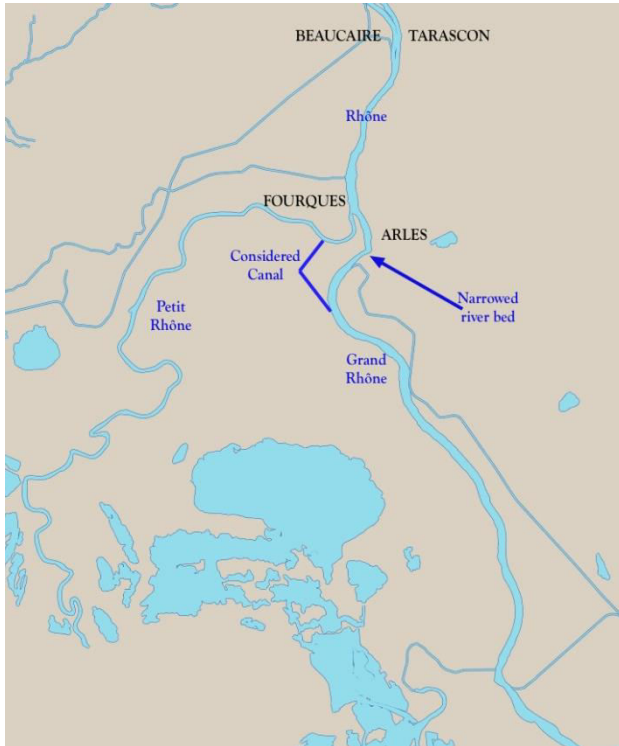


Figure 5. Project for a discharge channel between the Rhone and Arles (source: Rémy Tourment, Irstea).

The second scenario, which features a large movable weir at the canal's input, has no negative consequence on sedimentation, but also does not sufficiently address the objective of lowering the flow line in Arles and upstream. Furthermore, it raises the question of the maintenance of mechanical structures which would be operated less than once in a century, on average. To summarize, the proposed canal, despite its high cost and other drawbacks, does not avoid any of the structures planned by the Rhone Plan, and so was not accepted in the end.

In the United States, the downstream part of the Mississippi is entirely artificialized, essentially to allow navigation and protect the plain from flooding. Levees run along it nearly continuously. Downstream, due to gentler slopes, floods tend to overflow more easily. To avoid overflowing that could be harmful to the levees, three complementary diversion systems have been built and improved, following the river's morphological evolution. The most upstream one, the Old River Control Structure, a system comprising several channels and regulation structures, manages the Mississippi's constant diversion towards the Atchafalaya. This recent river (mid 19th century) results from the lateral displacement of one of the Mississippi's meanders towards the Red River, which captured part of its water flow, and is since known downstream as the Atchafalaya. Downstream from this first diversion, and immediately upstream from New

Orleans, the Bonnet Carré spillway diverts by way of a channel part of the flood flow towards Lake Pontchartrain, whose outlet ultimately ends in the Gulf of Mexico. Implemented for higher floods and located between both diversions, the Morganza Floodway also diverts part of the Mississippi's water flow towards the Atchafalaya. These diversions protect Mississippi downstream levees against overflowing, and in so doing protect the plain against flooding due to breaches, but also the river itself from being entirely captured by the Atchafalaya, which would be detrimental to the economy in the state of Louisiana, as well as to a large part of the United States, who depend on this communication path. All of these structures divert from the Mississippi's downstream water flow more than half of its flood flow (Fig. 6).

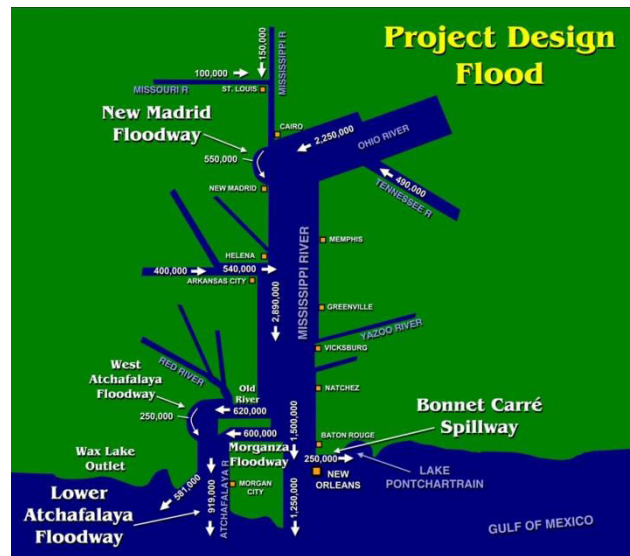


Figure 6. Flood flows of the Mississippi, of its affluents, and of its diversions (Source: USACE).

5 Flood Expansion Areas (FEA)

Flood expansion areas (FEA) pertain to the concept of dynamic retention [1, 9], which integrates a number of both management measures and structures located upstream of catchment areas, in order to reduce floods downstream. "A flood expansion area is an area where water naturally or artificially spills out in the event of a river overflowing from its bed into the flood plain. Temporary water storage induces flood attenuation by extending its flow time" ([5], p. 15). A flood expansion area should theoretically be an uninhabited area reserved for this purpose, which is the case amongst others of Rhine polders (Erstein and Moder polders on the French side of the border).

There are natural flood expansion areas (without works; watercourses and their flood plain in their non-structured state, preserved for allowing flood expansion), and areas protected by levees, but which act as flood expansion areas at the catchment area scale, because they are less protected than other areas, and finally, areas upstream of dams which unlike the other two types, can

be flooded higher than in the absence of the structure. The second kind of FEAs mentioned above are the most discussed due to specific interests and stakes. Given the important land use in France, these areas are actually inhabited rural areas (such as on the Rhône) that are protected from frequent flooding by levees, but to a lesser degree than other protected areas on the same watercourse that are more densely populated. Depending on the level of a given flood, the area may or may not be mobilized, which is actually the case for the entire flood plain.

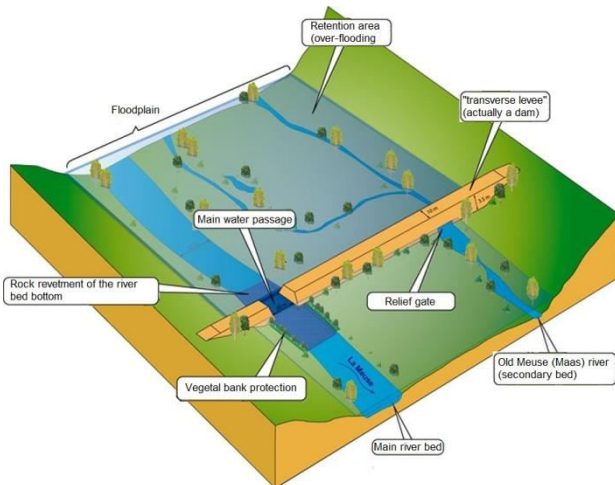


Figure 7. Mouzon's dynamic flood retention areas (DFRAs)
 Source: EPAMA).

Flood expansion is indispensable at a catchment area scale, and can even be considered as a watercourse's natural state... "Creating" areas dedicated to this effect is only necessary because watercourses have been rendered artificial and man, who has removed a relatively important part of flood plains from flood expansion, has exacerbated floods. The high floods of history, such as in the Mid-Loire Valley, with hundreds of breaches during the 1846, 1856 and 1866 breaches, remobilized "protected" areas in order to spread the floods which could not physically transit downstream.

Like diversion canals, FEAs lower flood levels downstream. The main difference between a canal and a structured FEA (such as a levee or a dam) is that a canal is limited by the diverted flow, whereas an FEA's volume will limit its filling time, and therefore, its effect. With lasting floods, using a flood expansion area is difficult because their mobilization must occur at the flood's peak, which involves carefully planning when infilling has to occur.

The difference between structured FEAs including protection levees such as Rhine polders or downstream Rhone FEAs and over-storage basin FEAs (EPAMA's Mouzon DFRA, Figure 7), is that the latter can flood larger surfaces than natural floods. In this case only, it can be said that there is over-flooding compared to a natural flood, both in terms of the flooded surface and of its height. Both kinds of FEAs using structures flood for longer periods than the natural flood, except in the case of

specific equipment aimed at accelerating post-flood drainage (sluices, pumping stations, ...). To avoid drawbacks caused by over-flooding or increased flooding durations, protection levees close to the highest stakes in a FEAs may be considered (close protection levees) in addition to the first line of levees. But they would have to be monitored and maintained just as well as first-grade levees, if not better, which is also a challenge, given their infrequent water loading.

Optimizing protection levels in flood expansion areas calls for cost-benefit analyses [6] to determine the level of protection for FEAs protected by levees. These should be carried out at both the scales of the FEA, and of the catchment area. The results of such cost-benefit analyses may in turn be used in multi-criterion analyses, introducing other non-monetary factors. In the Rhone Plan context, a project aimed at optimizing the protection of the Boulbon-Vallabrègues FEA ([5], p. 31), immediately upstream from Tarascon, is being studied. Many hydraulic factors, risk analyses and other considerations will be examined.

Keeping or "moving" levees far from watercourses presents many advantages, such as remobilizing natural flood expansion areas that had been lost until then (except during breaches, but this is then dangerous and unpredictable). Beyond this aspect, levee loadings, both in hydraulic and morphological terms, and hence in terms of erosion ([2], section 7.3), will diminish and lead to safer, possibly even lower levees. This principle has been adopted for the "third correction" of the Swiss Rhone, which advocates widening of the river bed between levees, reinforcing levees and implementing levees that are resistant to overflowing, as well as second rank levees (close protection levees). Watercourse movement areas lessen risks, and reintroduce a more natural space, hence improving the environment and biodiversity. This principle is also

6 Conclusions and perspectives

FEAs are not opposed to protective embankment systems or to diversion canals. On the contrary, they are often complementary solutions for the management of floods in catchment areas, and even on a more local level. Protective embankment systems allow protecting areas from flooding, with their own limitations in terms of level of protection. FEAs, however, reduce hydraulic loading of downstream levees and of upstream levees, respectively by lowering the water flow and by backwater effect. An FEA can also be protected, either partially or entirely, for a given flood level and thus be filled through spillways or overflowing resistant levees. Diversion canals are also solutions that lessen watercourse flows, although they call for appropriate outlets which can eventually be FEAs in particular cases.

Thus, as we can see these different solutions, often considered to be antagonistic, are actually compatible and not mutually exclusive. Furthermore, consistency

between these solutions has to be researched, at catchment areas scales, to optimize flood management. A multi-scale analysis is often necessary to establish a comprehensive analysis, from a local level and in terms of catchment areas [11]. This analysis can be based on a formalized risk analysis[13], eventually completed by a multi-criteria analysis [14].

To conclude, it will be important to ensure that the design and management of these structures are integrated, taking into consideration not only flood risks but also erosion, morphological evolution, and environmental objectives [12].

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