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CHAPTER 13

FRENCH EXPERIENCE WITH OPEN CHECK DAMS: INVENTORY AND LESSONS LEARNT THROUGH ADAPTIVE MANAGEMENT

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Abstract

The French torrent control service designed and has been maintaining, directly or indirectly by technical support, more than three hundred open check dams. These structures provide key protection services against torrential floods and debris flows. Some structures are several decades old and yet experienced several events of high magnitude. Until recently, design criteria were lacking, and these structures were designed empirically by intuition and trial and error. A detailed inventory was performed in 2017-2018 to gain knowledge on past experience and lessons learnt from these structures. This chapter recall basic knowledge on open check dam design, gives an overview of the existing structures in France and show statistics of the most frequent malfunctions and adaptations that were required. Three sites are described more in detail to exemplify typical situations where adapting management was performed. We hope sharing these lessons learnt based on past errors will prevent their repetition elsewhere.

13.1 Introduction

Within a torrential watershed, several complementary facilities can protect people, housing, networks and facilities against floods and debris flows. Classical closed-type check dams completed with reforestation and soil conservation bioengineering are very common in headwaters to prevent erosion near the source and stabilize streambeds and hillslopes (Evette et al., 2009; Carladous et al., 2016b; Piton et al., 2017). Closer from assets are found dykes, bank protection and open check dams interacting with solid transport, i.e., boulders, gravel and wood, before it reaches elements-at-risk (Hübl and Fiebiger, 2005).

Open check dams, also called sediment traps, open sabo dams, torrential barriers or debris basins, are widely used protection structures across Europe and Asia (Zollinger, 1985; Ikeya, 1989; VanDine, 1996). Historically, from the end of the 19th century onwards, some “places de dépôt” (deposition zones) were set up in European torrents but remained confined to limited volumes because they should be manually dredged (Eaux et Forêts, 1911; Vischer, 2003). Mechanically-dredged structures emerged just after World War II. However, in France, most open check dams were built during the 1980s and 1990s by the French torrent control service (ONF-RTM). The number of new construction decreased in France since the 2000s (Piton and Recking, 2016a). We started this analysis notably to understand why. The first hypothesis is a reduction in the financial resources allocated for building this type of structure, either directly by the State in State-owned lands or by subsidies for municipality projects. Second hypothesis is that maintenance experience sheds light on several problems such as downstream incision and excessive dredging costs. Third hypothesis is that design is not so easy in practice. A field general inventory and a second step of focus on structures on which lessons could be learnt and share were thus undertaken.

The used method of research involved four main steps. (1) A GIS general inventory of French open check dams, whose methodology is detailed in section 13.3.1, enabled to sort them according to storage capacity and main functions. (2) A more detailed inventory was implemented by field ONF-RTM officers for ‘large’ open check dams, i.e., with retention capacity > 1,000 m³. As explained in detail in section 13.4.1, data was gathered on design context, type of processes experienced, elements-at-risk, structural components, maintenance history, and malfunctions. (3) In-depth surveys on a dozen of selected structures involved a watershed analysis, description of local peculiarities, re-definition of structure objectives, and functional and structural analysis. By exchanging several specialists on the same site, this analysis of existing structures

enabled to identify the adaptations performed during the structure life so far but also those that would be necessary to improve its functioning, in view of the malfunctions observed or to be feared. Examples are provided in section 13.5. (4) Finally, the confrontation of this experience feedback with the recent development of scientific knowledge has made it possible to establish an approach not only for the design of new structures, but also for the diagnosis of existing structures. This point is discussed in section 13.6.2.

Reanalyzing failures through case-studies (Benito et al., 1998; Wang, 2013; Horiguchi and Richefeu, 2020), and malfunctioning of existing structures (Brochot et al., 2003; Bezzola et al., 2004; Bezzola, 2008; Chen et al., 2014; Wang and Kondolf, 2014; Yang et al., 2020; Mihalache et al., 2020) helps better designing new structures and anticipating suitable adaptation of similar existing ones. This chapter provides for the first time a perspective on the French experience in designing and maintaining open check dams. To the best of our knowledge, the only existing similar analysis at country scale is the report published by Hübl et al. (2005) in German on Austrian structures. Obviously, many uncertainties remain at each stage of this approach, but we hope that sharing our past mistakes and the lessons we learnt will prevent their potential reproduction elsewhere. The chapter first recalls what are the main functions and type of open check dams. It secondly provides an overview of the French inventory and the main malfunctions identified. It thirdly focuses on three examples of structure adaptations and finally discusses the main lessons learnt and our new design and diagnosis protocol.

13.2 Basic features of open check dams

13.2.1 Structure functions and control of deposition

Open check dams and sediment traps intend to control solid transport (boulders, cobbles, gravel and large wood) with the main goal of protecting downstream elements-at-risk as buildings and roads. To be more precise, four main functions can actually be achieved by open check dams (Bergmeister et al., 2009): (i) “sediment retention”, i.e. trapping of a given sediment *volume* before dredging (long term retention closed check dams are different structures, see discussion of Piton et al., 2019); (ii) “solid transport dosing”, i.e., sediment *discharge* buffering; (iii) “boulder trap”, also called debris flow breaker because they break *debris flow fronts* and store big *boulders* that would likely clog downstream narrow section; and (iv) “large wood traps” to store *logs* that would have a similar obstruction adverse effect.

Understanding of the processes leading to deposition is crucial to achieve such selective trapping. Zollinger (1985) highlighted that four mechanisms interact and eventually lead to deposition (Figure 13.1a). The first two mechanisms are driven by basin geometry. (i) An eventual slope break at the basin entrance results in a loss of flow energy and thus a decrease in transport capacity. (ii) The flow spreads if the basin is widened, dropping shear stresses and thus decreasing transport capacity too. The two other mechanisms are driven by the barrier. (iii) “Hydraulic control” refers to a delta-like deposition in the water accumulating upstream of the barrier during the event. (iv) “Mechanical control” refers to the blocking of elements that are too large to pass through the openings, especially boulders and large wood. Depending on the barrier and basin geometry and the type of torrential phenomenon, combination of these mechanisms may facilitate (or not) deposition.

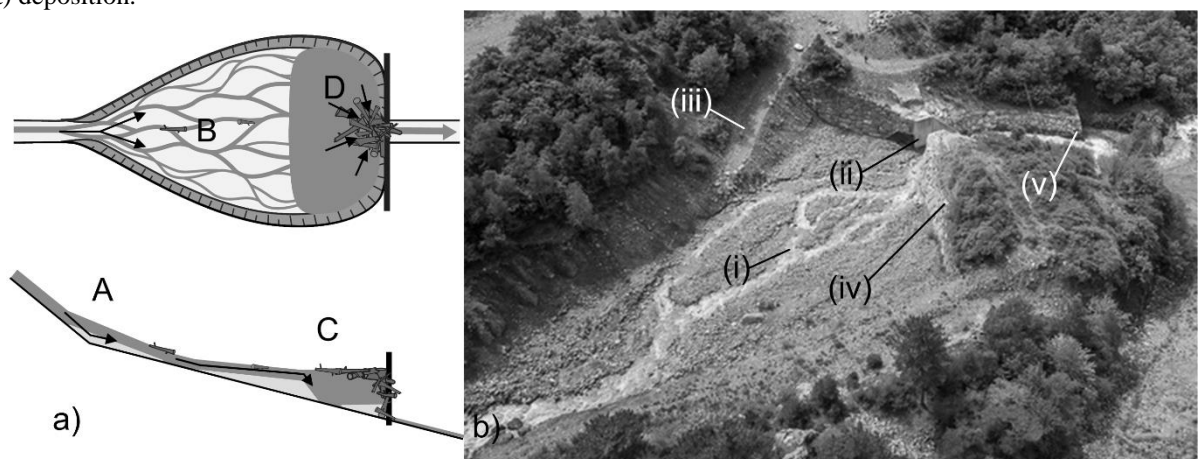


Figure 13.1: a) Schematic top view and side view of bedload depositing in a basin due to (A) slope break, (B) flow spreading, (C) flow velocity drop in the barrier backwater and (D) mechanical blockage at the barrier, and b) drone view of the Saint-Martin torrent upper sediment trap (Saint-Martin-la-Porte, France) with (i) deposition basin, (ii) slit barrier, (iii) access track, (iv) side dikes and (v) scouring protection. A natural slope break and upstream armored bed makes an inlet structure unnecessary (Picture courtesy of Alban Pernet)

13.2.2 Structure components

Natural slope breaks and/or widening of the streambed are consequently best-suited location for open check dams because sediment deposition naturally occurs in such areas. An open check dam merely increases the thickness and volume of the deposit (Van Effenterre, 1982). In addition to the basin and barrier, a sediment trap is made up of several components (Figure 13.1b), each having a specific function to achieve, as detailed in the French guideline of Deymier et al. (1995) inspired by Zollinger (1985):

- The basin (or deposition area) is where material will be stored, its trapping capacity may be modified by widening and / or reducing the bottom slope;
- The outlet barrier filters the solid discharge: its shape drives the main structure function (see §13.6.1);
- An upstream inlet structure eventually guides flows at the basin entrance and stabilizes the upstream streambed profile against headwards erosion if the basin is dredged too deeply;
- A scour protection prevents the scouring of foundations (at inlet foot, at barrier foot and eventually along certain portions of the side dikes);
- The lateral dikes confine and guide flows to the downstream outlet barrier and prevent its outflanking;
- An access track facilitates access to engines for maintenance operations.

Not all components are systematically encountered on every open check dam, especially on sites with natural channel confinement and / or bedrock outcrops. The basic features of any open check dams are a deposition basin, an access track and a barrier.

13.2.3 Design events

The previously mentioned trapping mechanisms vary with flood features as discharge and grain sizes. These parameters should be estimated for the whole range of events that the structure may eventually experience to design the various structure components:

- The "routine" events do not cause damage. Full transfer of water and solid discharge must be sought for these events to minimize maintenance. Barrier bottom opening and basin guiding channel are designed using routine event features;
- The "project" (or "design") event is used to design the trapping capacity and central part of the barrier in order to achieve one or more functions with freeboard;
- The "safety-check" events are used to design side dikes preventing lateral overflowing and a spillway preventing barrier outflanking which must be above and wider than the openings (5 m-wide slits cannot be considered spillways and are regularly obstructed by boulders up to the crest, e.g. Piton et al., 2020a). Safety-check events correspond to the range of events more intense than project events for which the structure should not failed;
- The "danger" event is used to raise awareness that above a certain magnitude, the structure stability is no longer guaranteed, and failure is likely to occur (but not sure). It is most of the time associated to barrier outflanking (zero freeboard on spillway wings) or barrier scouring excess.

It should be noted that this design process based on differentiating these different levels of events is very recent and inspired by standards on flood retention dams (Royet et al., 2010). There was a lack of specifications in technical guidelines available at the time of construction of most of French open check dams (the only known reference was Zollinger, 1985). In practice, the volume design was mainly guided by the last known event of high magnitude and the room available on the chosen site, without necessarily specifying a design event with a known return period. Concerned by chronic deposits, the designers tailored solutions empirically to limit material trapping during the routine events as e.g., guiding channel in basins (see Manival torrent below or e.g. Figure 7 of Piton and Recking, 2016a), bottom outlet (see Saint-Martin and Claret torrents below). In many cases, such adaptations were planned but not built due to lack of available funding.

13.3 Overview of the French existing open check dams

13.3.1 Selection of structures to be inventoried

Solid transport deposition and management also take place out of open check dams. The advent of earthmoving machines has favored regular clean-up operations in other areas: directly in steep reaches or at deposition areas (natural or upstream of closed dam). As this inventory aims at providing feedback on open check dams, dredged sites without outlet barriers were considered as "solid transport regulation areas" and were excluded of the inventory. Some open check dams are no longer dredged: these sediment traps became solid transport regulation areas. Their barrier now acts as classical closed check dams merely generating bedload transport regulation by transient deposit during high solid concentration event and latter spontaneous re-erosion (Piton and Recking, 2016b). This operational adaptation usually resulted from excessive maintenance cost and / or chronic downstream incision while residual risk was considered reasonable.

Finally, structures of more than 1,000 m³ and less than 1,000 m³ were differentiated: a detailed feedback was requested for the firsts, while only information on the location was collected for the latter.

Out of 394 structures located in French mountain areas (Northern and Southern Alps, Pyrenees), 330 were included in the inventory, excluding 28 solid transport regulation zones, 17 sediment traps transformed into solid transport regulation zones and 19 structures that have been removed from the inventory after field visit and checking of data availability.

13.3.2 Structure number: regional and temporal trends

About 50% of the 330 sediment traps inventoried have a retention volume < 1,000 m³, 22% are between 1,000 m³ and 5,000 m³, 26% are between 5,000 m³ and 50,000 m³ and 2% are > 50,000 m³. The Northern Alps host 79% of the total number and 73% of the structures larger than 1000 m³ (Figure 13.2a). They are several reasons to this higher concentration of structures in this region, among them a higher density of elements at risks, stronger influence of the past glaciation on valley geomorphologies inducing more frequent disconnections in alluvial systems and associated chronic sediment deposition issues (Carladous et al., 2016a, 2016b). For these same 330 sediment traps, 20 % are located in public forests having the specific status of Restoration of Mountain Land (RTM) and are maintained by the French State. All other sediment traps are under the responsibility of the local authorities.

The construction date is known for 311 of the 330 selected structures. Figure 13.2b highlights the clear growth of structure number during the 1980s and 1990s, but also the decrease in their construction rate from the 2000s onwards. This slowdown is likely due to several reasons: the investment cost was too high in relation to the available financial resources; the maintenance efforts proved to be higher than expected on existing structures (see next section); the difficulties in real estate acquisition to build these structures, as well as increases in regulatory constraints both on land development (the rule used in France was not to allow new urban development even though open check dams or other protection measures were built, in fear of their failure – see Philippe et al., 2016) and environment: in line with the EU Water Framework Directive and the concept of sediment river continuity (Habersack et al., 2017) wherever it is possible, dredged sediment must now be replenished downstream, which is also more expensive. Note that for alluvial fans disconnected from downstream rivers, whether naturally due to river migration or artificially because of river embankment, sediment connectivity is lost and chronic deposition with higher torrential hazard is the rule (Harvey, 2012). In such cases, trapping sediment and stabilizing sediment sources is the only solution to protect elements at risk located on the fan. The biggest cluster of structures that can be seen on Figure 13.2a is for instance located in the wide Isère alluvial plain where many torrents flow in drainage ditches with slope so gentle that it cannot accommodate any bedload transport. The only other option would be to abandon these sites and to let the whole alluvial fan grow again until sediment connectivity is recovered.

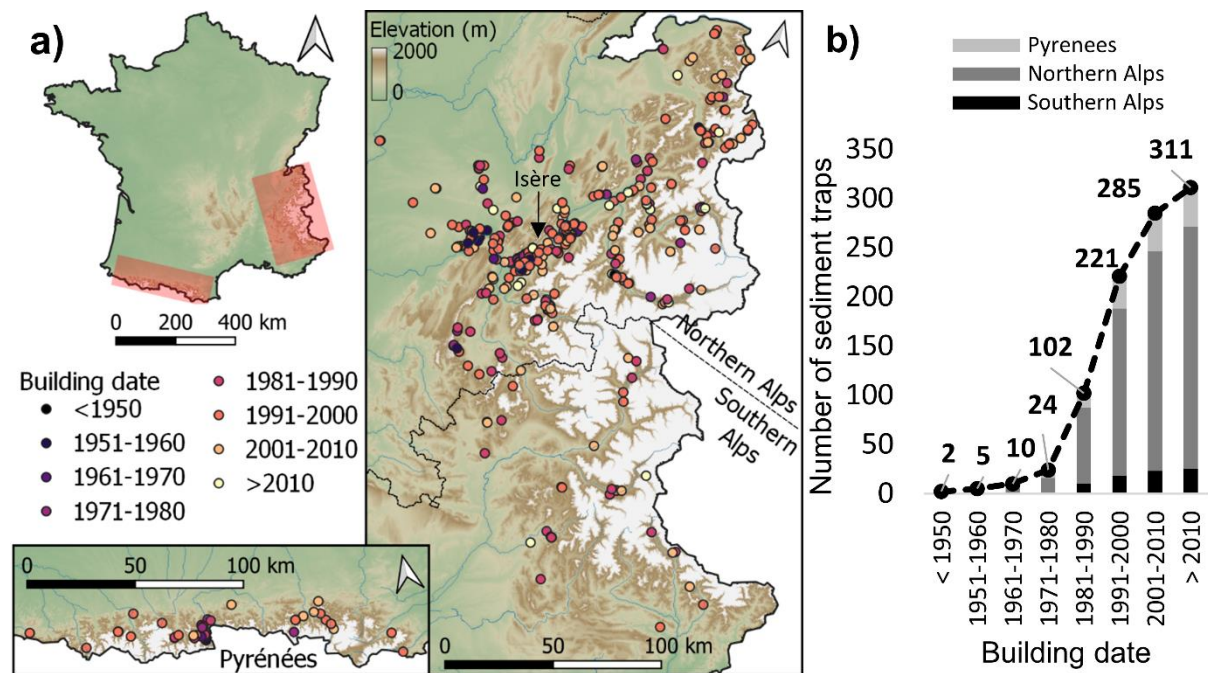


Figure 13.2: a) Location of structures inventoried and b) cumulative evolution over time of open check dam construction in France (all volumes combined).

13.3.3 Type of structures

Barriers can be equipped with basal or full opening (one or several slits or slots), partially or totally closed by grills (Figure 13.3).

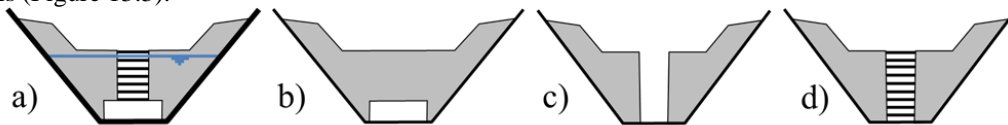


Figure 13.3 : Elementary types of opening in barriers: a) slit dam with horizontal bars and a basal slot; b) slot dam; c) slit dam; d) slit dam with horizontal bars (adapted from Piton and Recking, 2016a).

Among the 164 sediment traps larger than 1,000 m³, 60% are equipped with bars in the barrier openings, the most common configuration being horizontal bars. Seventeen percent of the barriers are slit dams, most of them being single slit. Finally, 11% are slot barriers, horizontal slots (i.e., width > height) being almost not used. Some techniques are found only in certain regions: arch dams with bottom openings (nozzles, small gutters) for instance in the Luchon's valley (Pyrenees) where ONF-RTM officers were inspired by flood retention dams.

Rudolf-Miklau & Suda (2011, 2013) suggest now in Austrian standards to use series of open check dams on torrents; each structure having a specific function tailored to the site peculiarities: e.g., trapping boulder and large wood first and secondly a retention structure (e.g., Cerato and Coali, 1997). This is not the choice that has been made so far in France because of budget limitations.

The function of 95% of the inventoried structures is sediment transport retention. It highlights that the practice in France was conservatively to seek trapping most of solid volume transported by floods. Lacking comprehensive design criteria, designers selected conservative options: it was thought better to trap too much sediment than too little. However, after several years of operation, chronic and regular deposition was observed on most structures (see §13.4.3). This led to the two main undesirable side effects (Gruffaz, 1996; Brochot et al., 2003). (i) Sediment starving downstream of structures triggered rapid incision, scouring of banks and of bridges and weirs, requiring to build series of new check dams and/or a flow channel with a solid apron downstream of the sediment trap to stabilize the stream bed and avoid its incision. (ii) Often immediately after complement, high frequency of dredging and its cost often called into question the fact of allowing more sediment to pass through, which was considered uncertain, potentially dangerous due to insufficient understanding of the processes at work, and thus rarely done until recently (see §13.5). It should be stressed that French open check dams were built before the publication of most scientific works dedicated to this topic. Consequently, in most French sites, a single structure is often intended to perform several functions, e.g., a large retention structure will also trap boulders, cobbles, gravel and large wood with poor control of the interaction that may emerge (see e.g. Piton et al., 2020b).

Only three structures inventoried were designed with the specific function of boulder trap and three other aims at dozing solid transport. Ten large wood traps were inventoried but a complementary inventory would be necessary because many other of these structures are also located on small rivers, upstream of small hydraulic structures (culverts, pipes).

13.4 Maintenance feedback

13.4.1 Template form for structure inventory

In order to conduct a general appraisal on works, a template form was drawn up and divided into seven sections:

1. General: geographical location (department, watershed name), construction administrative elements (year of construction, project managers, designer), precise location (altitude, GIS coordinates).
2. Natural phenomena: upstream catchment features (geomorphological parameters, vegetation cover, geology, type of most common torrential phenomena), natural phenomena (main event that led to the creation of the sediment trap, design events), grain sizes of the supplied material.
3. Elements-at-risk: protected elements (housing, networks) that may be affected by torrential phenomena in the absence of the structure.
4. Existing complementary torrent control structures: general description of complementary works located both upstream and downstream (drainage, diversion, check dam series, dykes, other sediment trap); detailed description of the structure itself (assigned function, initial and current retention capacity, barrier outlet features and, if present, upstream inlet structure and side dikes).
5. Management and maintenance of the sediment trap: history of past dredging (years of completion, cost, inputs stored in the sediment trap during each flood, volumes of material dredged and their destinations); list of maintenance or modification/improvement works.

6. Malfunctions: list of the major malfunctions observed or foreseeable during future events and/or in the long term. The adaptations implemented or to come on the structure are also described.
7. References: main existing studies, officer and date of filling, availability of pictures, plans and topographical data.

Parts 1 to 4 are a simplified, but factual, description of the structure environment, the torrential hazards it is supposed to act on and the functional characteristics, particularly of the barrier. Parts 4 to 6 identify malfunctions that occurred or are expected. Adaptations are most often proofs of malfunctions, ill-design or misunderstanding during the design. It must be stressed that malfunctions observed or foreseeable can affect both the sediment trap and its side effects, for instance on the downstream channel. For instance, if one of the downstream structures was implemented after the sediment trap, it may indicate a malfunction of the latter. Excessive dredging costs can also be seen as a malfunction, sometimes leading to an operational failure. The capacity of the structure to meet the expected objective was also reported in order to identify any malfunctioning of the entire structure rather than of its components. With the available time and data, inventory sheets were completed by the ONF-RTM services for 115 out of the 164 structures with a retention capacity > 1,000 m³.

13.4.2 A good opportunity to appraise costs of dredging

Dredging cost can be a large share of the structure total cost at the life cycle timescale. The inventory was a good opportunity to gather data on the cost of cleaning and dredging open check dams. Only dredging operation with volume bigger than 1000 m³ are considered: for smaller volume, costs are more driven by the flat rate costs related to bring the earth moving machinery on the site than by the actual volume to dredge.

Figure 13.4 shows that what is made of the material, i.e., its destination, plays a key role on dredging costs. The most expensive (median value of 14 €/m³) is to replenish sediment in the downstream river system in order to maintain river quality status, though we only have five data. Conversely, whenever the trapped sediment is of sufficiently good quality to be reused for construction purpose, it is much cheaper (median value of 3 €/m³). It can be done for free or even against payment for extremely good material (such cases were considered exceptional and not considered). Evacuation, partial replenishment or storage on site are in between these two extreme cases. Note that large data sample are available only for material that was reused or evacuated. The variability in dredging cost can be explained by e.g. exceptionally high cost to bring the earth moving machinery on remote sites, variable ease of dredging the material (granular material is easier than muddy), distance on which material must be transported on access tracks of very variable quality or necessity to open new access tracks on rarely dredged sites.

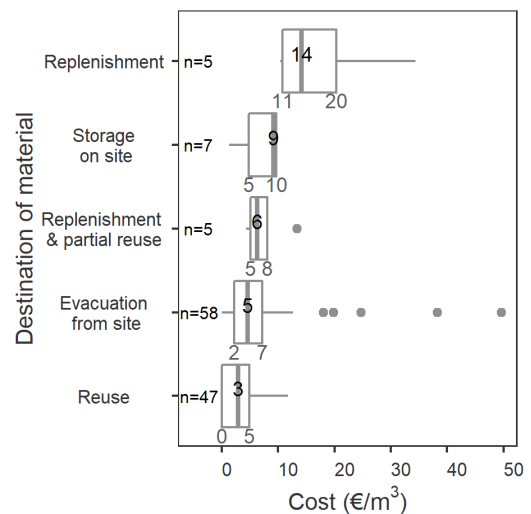


Figure 13.4 : Variability of dredging costs depending of destination of the excavated material for n = 122 dredging operations in several open check dams from the Alps with volume dredged > 1,000 m³. The central mark and black number in the boxplot indicates the median, and the left and right edges and grey numbers indicate the 25th and 75th percentiles, respectively.

13.4.3 Most frequent malfunctions identified

Of the 115 detailed inventory sheets completed, no malfunction was noted for 67 (58%) of them. This can be explained by i) the good functioning of these structures, but also ii) by the fact that some malfunctions could be considered as minor and did not deserve to be noted or iii) by the absence of stresses on these structures, for instance if no event of major or moderate magnitude occurred since their construction. Table 13.1 summarizes the malfunctions reported on the 48 other structures. It differentiates the malfunctions, their potential causes and related consequences. Malfunctions called differently but actually similar were grouped together. Overall, about twenty types of malfunction (observed or foreseeable) were extracted and can be clustered into seven main types (hereafter noted as ‘MF’). Note that some structures experienced several malfunctions. The consequences identified are the direct consequences without an analysis of the real consequences on downstream elements-at-risk (residual risk analysis including the occurrence of the malfunction) having been carried out: this would be an improvement to be made.

According to Table 13.1, the main malfunctions identified are 38 cases, i.e., one third of structures, of excess in trapping, especially during routine events, leading to a chronic decrease in the retention capacity (MF#1, Figure 13.5a) or to stop dredging because this maintenance is too expensive (MF#6, Figure 13.5b) ; 21 cases (18% of structures) of barrier outflanking (MF#1, Figure 13.5d); and height cases (7% of structures) of poor location resulting in incision downstream (MF#3, Figure 13.5c). Conversely, only seven cases of barrier structural damage were reported, although it attracts much of the current research effort. Operational or functional failures are actually much more frequent.

Table 13.1: List of identified malfunctions, the associated causes, the consequences and the number (n) and frequency (freq) of case reported among all detailed inventory sheets

Malfunctions	Causes	Consequences	n (freq)
MF#1 Trapping excess: stopping of materials and filling for routine event (Figure 13.5a)	<ul style="list-style-type: none"> - undersized slot - vertical bars or slots down to the invert - openings/channel section too small - opening/side channel clogged by cobbles or large wood - not steep enough - oversized/too large basin - poor location on the longitudinal profile 	<ul style="list-style-type: none"> - incision downstream (Figure 13.5c) - maintenance too expensive (cf MF#6) - decrease in retention capacity prior to an upcoming project event 	38 (33%)
MF#2 Outflanking of the barrier (Figure 13.5d)	<ul style="list-style-type: none"> - the height of the deposit near the inlet is too high compared to the height of the lateral dikes - lateral avulsion upstream of the inlet - access track built to low in the dikes - wing slopes and dyke crests too low - dynamic side overflow - barrier spillway too small 	<ul style="list-style-type: none"> - trapping failure or partial (cf MF#5) 	21 (18%)
MF#3 Location too far upstream of element at risks	<ul style="list-style-type: none"> - land constraints - easier realization (land, financial) on State land (RTM policy) than on municipality or private land 	<ul style="list-style-type: none"> - incision downstream - bypassing the structure because the deposit is too steep - hazard can be due to downstream material recovery (cf MF#7) 	8 (7%)
MF#4 Structural damage on the open check dam	<ul style="list-style-type: none"> - steel bars damages / destroyed by impacts of boulders - material wear - soil compaction - lateral dike erosion 	<ul style="list-style-type: none"> - lower structure stability and/or durability 	7 (6%)
MF#5 Insufficient storage capacity	<ul style="list-style-type: none"> - unsuitable location on the longitudinal profile - deposition slope lower than the design slope for the design event - reduction of the capacity by frequent bedload transport - available space limited by land constraints - limited construction budget - lack of knowledge of the design event volume 	<ul style="list-style-type: none"> - deposit in the downstream channel - formation of a plug at the confluence with the main river downstream 	6 (5%)
MF#6 Lack of maintenance: no more dredging or a long period without dredging after an event (Figure 13.5b)	<ul style="list-style-type: none"> - access difficulties, no access - location too far from elements-at-risk upstream - materials of poor quality, non-reusable - storage space limitation - very costly transfer - systematic deposit leading to very costly dredging 	<ul style="list-style-type: none"> - systematic reduction of actual structure retention capacity 	4 (3%)
MF#7 Transfer of debris flows downstream of the structure	<ul style="list-style-type: none"> - location too far upstream from elements-at-risk and re-erosion of the intermediate reach 	<ul style="list-style-type: none"> - ineffective protection 	1 (1%)

13.5 Three cases of adaptive management

As shown in Table 13.1, the most reported malfunction is the excess of trapping, especially during routine events. It usually results in significant dredging costs and in bed incision downstream (Gruffaz, 1996; Brochot et al., 2003). Adaptation as functional modifications were then made to some structures to cope with this issue (e.g., Piton, 2016, p. 53). We provide hereafter three detailed examples.

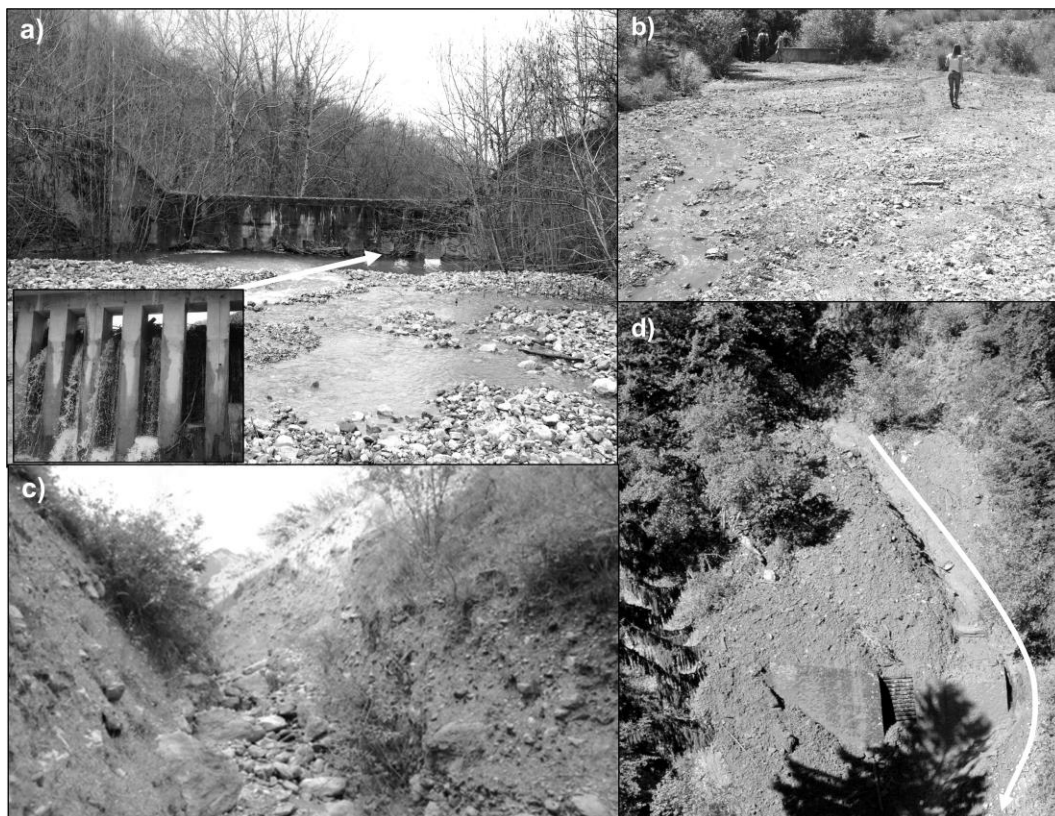


Figure 13.5: Illustration of main malfunctions identified for sediment traps: a) decrease in the retention capacity due to wood logs frequent clogging in the Lavanchon torrent (Saint-Paul-de-Varces, France); b) no more too costly dredging in the Clavaux torrent (Barcelonnette, France); c) location too far from elements-at-risk upstream and stopping of materials and filling for frequent floods resulting in downstream bed incision in the Manival torrent, (Saint-Ismier, France); d) bypass of the open check dam by right side in the Castelvieil ravine (Luchon, France)

13.5.1 Where not to put grill in slit dams

The Saint-Martin torrent experiences a debris flows event on average every seven years (ONF-RTM 73, 2013a, p. 38; Piton et al., 2020a). The downstream fan channel is located near residential areas and crosses several local roads and the France-Italy highway on a canal bridge. The risk is mainly due to eventual channel obstruction by boulders of diameter 3-6 m. Such boulders can be found on channel banks and spread across the entire fan (Hugerot, 2020). The current protection strategy mainly relies on two sediment traps and an artificial channel on the alluvial fan to transfer debris flows to Arc River. The upper sediment trap, with a retention volume of 10,000 m³, was built by the State in 1986-1987. *Figure 13.6* reports the structure's history: building, adaptations and events. The building by the highway manager of the second lower sediment trap in 1995 can be seen as an adaptation to increase the capacity of the global protection system. It is also an example of the easier realization on State land than on municipality land (Table 13.1, MF#3): the initial project for the implementation of the first structure, located in State land, was at the location of the second one (municipality land).

After the two successive debris flows of 1993, the most important adaptation was to decide not to replace the grill in the slit: the former grill dam became a single slit dam (see Adaptation #2 and description of 1993 events in *Figure 13.6*). This experience led local practitioners to consider slit dams as relevant solutions in debris flows prone watersheds where flooding and damages are not due to the debris flow overall volume that can be damped by the confluence; in these sites, problems rather occur (i) if huge boulders may stop in the channel and obstruct it, for instance at bridges (in this case the slit dam can trap boulders), or (ii) if the instantaneous flow discharge is much higher than the fan channel capacity (in this case the slit dam can dose, i.e. buffer the discharge). The protection system functioning was considered satisfying for the five debris flows observed since this adaptation. Slit obstruction sometimes occurs, but events without blockage, are more frequent (*Figure 13.6*). In addition to the previous functional adaptation, damage was observed on the slit apron and on the barrier downstream face during overflowing. This led to several structural reinforcements with stone pitching and steel plates.

Moreover, it is worth stressing that field observations after five different debris flow events brought evidences of the solid transport dosing function in the second downstream slit dam (Adaptation #3 in *Figure 13.6*). This structure was designed as a 5 m-wide slit dam from the start, i.e. same width than the upstream barrier. Since its construction in 1995, much lower dredging is required than in the upper dam (10,000 m³ in 2011). One could believe that the dam was never filled but mud marks were observed, sometimes showing slight spillway overflowing, indicating temporary storage during surges. It is however reckoned that the choice of a slit width identical to that of the upstream open check dam does not offer any additional safety with regard to the risk of transit of large boulders, a smaller opening than the upstream one would be better.













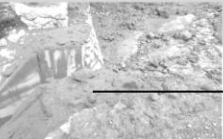
Date or year	Operation	Event and observation
1986	Building slit dam and grill	
1987	Adding of lateral dikes with stone-pitching protections	 - Chronic deposition of bedload transport during routine events
1989	Adaptation #1: adding of a 1m-high bottom clearance to avoid trapping routine events	
01/07/1993		 - Debris flow, barrier overflowing, grill destroyed & self-cleaning (dredging cost only 5,000 m ³) without damage (not foreseen but considered interesting)
07/07/1993		 - Debris flow (15,000 m ³), slit obstruction by a huge boulder (104 m ³), filling of the basin, barrier overflow and side dyke marginal erosion
1995	Adaptation #2: grill not replaced Adaptation #3: adding of a second slit dam downstream	
1996	Adaptation #4: reinforcement of the structure (steel plate upstream, anti-scour downstream)	
03/22/2001		- Debris flow (4,000 m ³), no slit obstruction
06/22/2005		 - Debris flow (18,300 m ³), slit almost fully obstructed by boulders, near total filling of the basin, downstream bed erosion
02/08/2007		 - Debris flow (4,280 m ³), no slit obstruction
02/07/2010		 - Debris flow (14,000 m ³), slit obstruction by large boulders, downstream bed erosion and damage on the counter-check dam
08/22/2011		 - Debris flow (4,280 m ³), no slit obstruction but damage downstream
2011	Adaptation #5: downstream protection against erosion with guiding channel and reinforcement of the existing counter-check dam (height = 7,5 m)	
2012	Adaptation #6: Adding of wings over the slit to guide flows during overflowing events	
07/01/2019		 - Debris flow (20,000-35,000 m ³), spillway overflowing, no slit obstruction but overflowing on the highway canal bridge

Figure 13.6: Historical design, technical adaptations and events experienced by the upper sediment trap of the Saint-Martin torrent (Saint-Martin-La-Porte, France)

13.5.2 Cutting a slit in a slot dam

The Claret torrent experiences a debris flows event on average every two-three years (ONF-RTM 73, 2013b; Hugerot et al., 2017). This tributary of the Arc River crosses and threatens several strategic infrastructures: a doubled-culvert passing below a large canal supplying a hydro-electricity power plant, a departmental road bridge, a canal bridge over the France-Italy highway, the France-Italy railway bridge and another departmental road bridge before the confluence. A factory is additionally located right in front of the torrent mouth, on the left bank of the confluence and was several times flooded when debris flows dam the river. Here also, problems on the fan channel occur mostly when large boulders obstruct any of the many crossing structures. Conversely, near the confluence, flooding and damage occur if the debris flow volume exceeds the confluence buffering capacity, dam the Arc River and eventually triggers channel backfilling in the river and torrent beds.

The current protection strategy mostly relies on an artificial channel conveying debris flows to the Arc River, and on a sediment trap built by the State in 1991, after a significant debris flows in 1987 that caused the obstruction of the doubled-culvert under the hydro-electricity canal and a beginning of overflowing in it. Its retention volume is estimated to be 25,000 m³, which is actually only about a 10 years return period event, i.e., closer from routine events than from a project design event with return period of a century or more.

The barrier was initially equipped with a 1 m x 5 m bottom outlet and an intermediate 1.5 m x 3 m slot (Figure 13.7a). Facing excessively high dredging costs (on average 17,000 €/year for 6,000 m³ dredged/year between 1991 and 2018) and following the lesson learnt on the Saint-Martin torrent (§13.5.1), the ONF-RTM service proposed, yet in 1995 and again in 2001, to increase the barrier opening into a large slit dam. The managers of the downstream elements-at-risk refused the adaptation but agreed to provide financial support to the dredging operations.

During the major flood of 2008, the Arc River experienced significant incision, thus increasing the confluence buffering capacity. A third study by Koulinski (2011) recommended again to increase the barrier opening sufficiently to allow routine event (partial) transfer. The slit should however still trap the large boulders prone to obstruct the downstream structures. After much negotiation and administrative procedure, the work was completed in 2018 (Figure 13.7b). Two criteria were finally used to define the 4 m width slit: (i) it was sufficiently narrow to trap boulders with diameter bigger than 2-4 m (mechanical blockage criterion), and (ii) the total slit section was about the same than each of the doubled-culvert located downstream (hydraulic blockage criterion). Thus, what passes the slit should normally pass the whole fan channel.

Since the cutting, the structure experienced two debris flows on 06/17/2019 (very low magnitude) and on 07/01/2019 (10,000-20,000 m³). During the latter, only a few large boulders (2 to 5 m³) and a limited volume of material (1,000-2,000 m³) remained in the basin. Nearly the whole debris flow was transferred to the confluence with the Arc River without damage. The deposit was reworked by earth moving machinery to ease their recruitment by the river flows, but at a much lower cost than dredging the sediment trap. The whole system thus functioned as expected. The open check dam is equipped with a monitoring system including a camera and we hope to gather useful data during the next events and compare them with the former functioning (Piton et al., 2018a).



Figure 13.7: Recent adaptation of the open check dams in the Claret torrent (Saint-Julien-Montdenis, France): downstream views in 2018 a) before (initial design) and b) after modification

13.5.3 Adapting basin shape and slope: adding a guiding channel with a steeper slope

The adaptation made on the sediment trap of the Manival torrent (Saint-Ismier, France) rather concerns the basin geometry. It is a good example of creating a guiding channel in the basin to promote routine event transfer, knowing that this idea had already guided the initial design of the Saint-Ours torrent's sediment trap (Val d'Oronaye, Alpes-de-Haute-Provence).

More than ten thousand peoples live on the Manival alluvial fan. The State has been building and maintaining a huge protection system in this catchment since the 19th century (ONF-RTM 38, 2016). It is a kind of text book case of the French torrent control approaches: longitudinal dikes on the alluvial fan (1830 to 1870); dozens of check dams to stabilize headwaters (1890 to 1940); two "V"-shape dikes built in 1926 to confine flows in a natural deposition zone (Figure 13.8i and ii); an open check dam, with five vertical slots, created in 1992 to increase the trapping capacity of the basin confined by the V-shape dikes (Figure 13.8vi).

A downstream bed incision was quickly observed (Figure 13.5c and Figure 13.9) due to routine bedload transport fully trapped by the structure (Piton et al., 2018a): i) the slope break (Figure 13.1aA) was too important after the dredging operations which promoted the upstream material deposition during the most frequent events; ii) for less frequent events (without being at the level of the design event), the reaching of the barrier with too narrow slots, in addition to a too wide basin, promotes mechanical blockage at the barrier (Figure 13.1aD). Given this downstream incision, dozens of check dams had to be built downstream in 1999-2000 and later reinforced to stabilize the profile (Brochot et al., 2003). If we consider the protection objective, the retention capacity of the sediment trap is 15,000 m³ compared to a retention requirement of 15,000 m³ for events with a return period of about 100 years and 30,000 m³ for rarer events, to avoid downstream damage by overflowing (ONF-RTM 38, 2016).

The study undertaken by ONF-RTM 38 (2016) proposed a first stage of adaptations, initiated in 2017, with two main goals: i) upstream the sediment trap, to increase the overall retention volume to 30,000 m³ for the design event (in this case, rarer than the 100 years return period) by storing 15,000 m³ of additional material through a promoted lateral overflowing towards an area without any elements-at-risk (forested zone upstream of the basin in Figure 13.8a); ii) on the sediment trap, to promote routine event transfer while ensuring deposition for less frequent events. In essence, the latter adaptation transformed the basin into a so-called "parallel trap" or "derivation trap" on which the basin can be excavated deeply because it is located on the side of a guiding channel (see e.g. Ghilardi et al., 2012). An inlet structure was added to be obstructed by big boulders and thus divert design events toward the side basin (Figure 13.8iv), a dike was built to form a guiding channel confining routine events (Figure 13.8v), and the basin was excavated deeper than before to maintain the former storage capacity (Figure 13.8vi). Since 2017, the sediment trap is monitored (Piton et al., 2018a) to get feedback on the new functioning of the basin. If additional increase in sediment transfer is desirable, a second stage of adaptation could be to widen the barrier slots, as in the case of the Saint-Martin and Claret torrents.

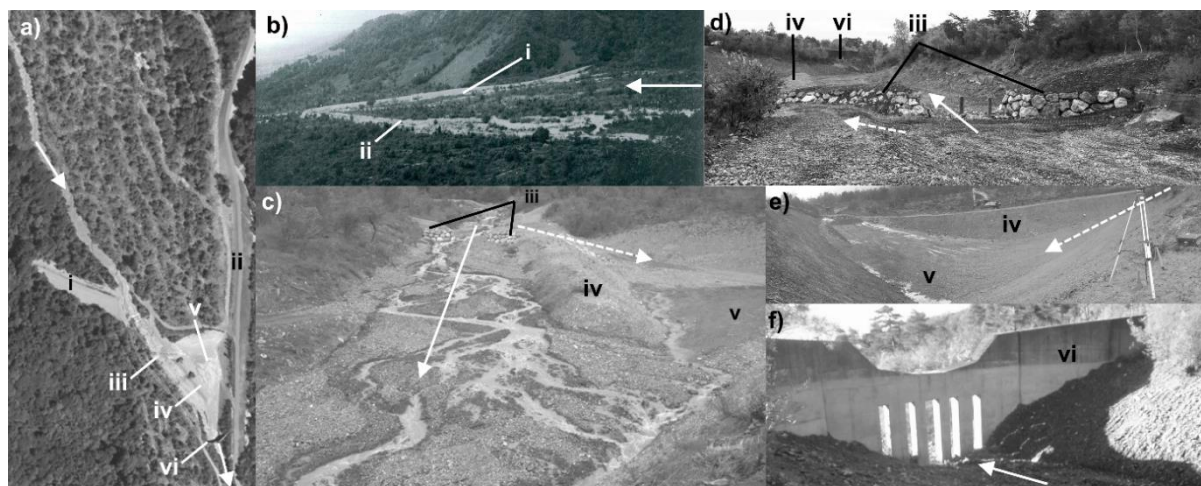


Figure 13.8: Recent adaptations of the sediment trap basin in the Manival torrent (Saint-Ismier, France): a) aerial view for localization of all the components of the sediment trap with (i) the right bank dike, (ii) the left bank dike (iii) the flow deflecting inlet structure, (iv) the guiding channel left bank, (v) the excavated lateral basin and (vi) the downstream slot barrier; b) far side view of the V-shape dikes in 1929, c) view from the barrier toward the basin during a routine event with white arrow showing flow trajectory for routine event (continuous line) and design event (dotted line), d) upstream view of the deflecting inlet structure, e) side view of the basin and guiding channel outer flank (photo during works in 2017), and f) the outlet slot barrier built in 1992

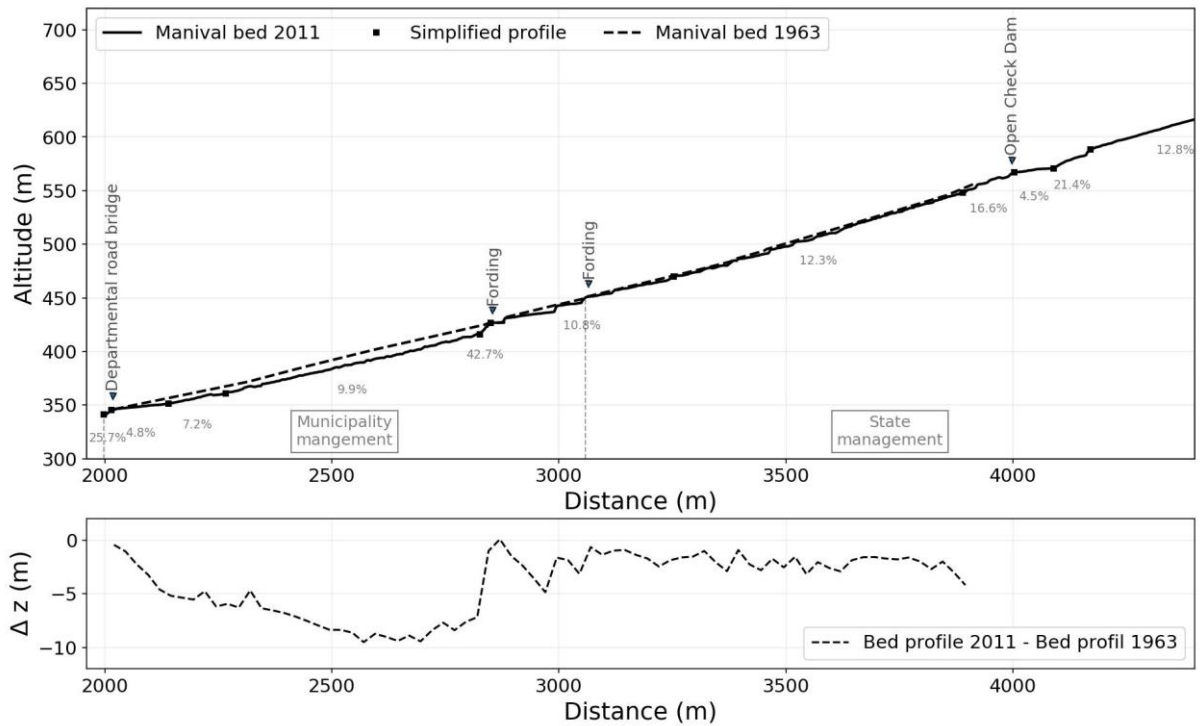


Figure 13.9: Longitudinal profile of the Manival bed downstream of the sediment trap in 1963 and 2011 (upper panel) and change in bed level ΔZ between the two dates (lower panel): incision reach up to 10 m (adapted from ONF-RTM, 2016).

13.6 Discussion

13.6.1 Selection of opening size adapted to structure function

As reported throughout this entire chapter, selecting the suitable function to a structure and the proper associated opening size is crucial when designing open check dams. According to field and laboratory works, the quantile 95%, noted D_{95} , is a relevant proxy of the diameter used for the design (Shima et al., 2016; Moldenhauer-Roth et al., 2021). Actually, selecting the opening size is both a matter of choosing which material should be trapped, but also which material should not be trapped. We thus recommend appraising:

- The size of *boulders that could not pass the downstream channel and bridges* (hereafter D_{dw}): if the torrent seems able to recruit and supply such boulders, the barrier openings should be small enough to ensure their trapping;
- The size of *cobble, gravel and small wood typically transported down to the downstream river system for routine events* (hereafter D_{freq}): openings should be designed to allow D_{freq} to pass otherwise chronic deposition will occur with many costly side effects.

Table 13.2 is an attempt to associate criteria for the barrier and basin design according to open check dam functions.

Table 13.2: Potential functions of sediment traps and associated barrier and basin features and design criteria

Structure type	Function description	Barrier opening(s)		Basin		
		Type	Design criteria	slope break	volume	Criteria
Sediment retention	stopping and temporary storage of transported materials until dredging	grid or slots, or even slit(s)	Small enough to be clogged by the transported materials ≈ max spacing of typically 1.5-2 times D_{freq}	marked	large	volume of material to be stored before artificial dredging
Solid transport dosing	reduction of the peak flow rate of transported material and spreading of the solid volume transit over time	slit(s) or even slot(s)	As large as required and possible: total spacing driven by instantaneous flow rate, each opening being narrower than 1-1.5 times D_{dw}	limited	large	volume of materials to be stored before recovery and self-cleaning
Boulder trapping	stopping and storage of large boulders only	one or several slits (preferably several)	Very large, typically opening width ≈ D_{dw}	none	limited	volume of boulders to be stopped before evacuation by excavators
Large wood trapping	stopping and storage of large wood that may obstruct downstream sections (size adapted to downstream capacity)	vertical bars or inclined grid dam or net	Large enough to allow gravel to pass (i.e., $\gg D_{freq}$) but narrower than 1/3 times large wood length	variable		volume of driftwood and upstream material to be stored before artificial dredging

We think important to stress that designer must take into both sediment and large wood in their design. Even though most open check dams were not built first to trap large wood, wood pieces are regularly supplied by active torrent (Ruiz-Villanueva et al., 2019), interact with barriers (Cerato and Coali, 1997; Bezzola et al., 2004; Piton et al., 2020b) and too often disrupt sediment transport during routing events (Figure 13.5a). According to the guidelines of Table 13.2, in typical cases, retention structure should trap 0.2 – 0.5 m-cobbles, thus and opening should be 0.3 – 0.75 m-wide if one consider 1.5 times the grain diameter. Such narrow widths are easily clogged by branches and logs, even during quite low flows transporting small pebbles. To allow routine flow to pass, the best option it to add a well-designed bottom outlet under grids with vertical bars, under vertical slots or under the first bar of grids with horizontal bars (Piton et al., 2019b; Moldenhauer-Roth et al., 2021) or to add an upstream small structure dedicated to large wood and boulder trapping (Cerato and Coali, 1997).

For sediment transport dosing structures, openings must be designed so that they are not blocked by large wood (Piton and Recking, 2016c). To achieve this, possible solutions include (i) setting an inclined grid of vertically oriented bars upstream the structure: water pressure causes the logs to rise along the structure, allowing sediment to pass underneath (Cerato and Coali, 1997; D’Agostino et al., 2000; Bezzola et al., 2004) or (ii) a protective crested siphon or net immediately upstream of the structure (Bezzola et al., 2004; Lange and Bezzola, 2006).

13.6.2 Design and diagnosis general recommendations

Given the main malfunctions observed, an approach was created to guide the design or adaptation of structures (Table 3, adapted from Piton and Recking, 2016a). A first step of analysis is carried out at the catchment scale to determine the protection objectives, the usefulness of creating a sediment trap and its possible location on the longitudinal profile (steps #1-#6). The design is then detailed at the scale of components (steps #7-#14). The last step (#15) consists in a cross control of the project feasibility and

consistency (spillway, dike height and closure check dam height): if some inconsistency are found, one must iterate with another design option or a revised objective (function or magnitude of the design event).

Table 3 gives the design general steps without technical and calculation details: a comprehensive review can be found in Piton and Recking (2016a, 2016c) for functional design, in Bergmeister et al. (2009); Rudolf-Miklau and Suda (2013) and Hubl et al. (2017) for structural design, as well as in new publications regularly improving these guidelines. We wish to highlight here the logic of the approach: if it seems theoretically obvious, it is not so obvious to implement in practice. Indeed, many land, environmental and cost constraints drive project designs. There are for example sediment traps located too far upstream due to land constraints (step #4), and barriers with too small openings because of over-conservative choice unsuitable to the upstream supply and downstream channel (step #2). The non-differentiation between routine and project event scenarios (step #1) for the dimensioning of the opening (steps #8 and #9) trigger problems in one third of structures. An insufficient longitudinal slope of the dikes (step #12) in relation to the height and slope of potential deposition (step #7) trigger outflanking of several barriers. Finally, compensatory measures for long-term side effects are sometimes lacking (step #14) due to an excessively high project investment cost (step #3).

All these observations on existing sediment traps have finally led to the formalization of this approach also applicable to existing structures. It is based on a resumption of a design approach, from the catchment analysis, the identification of the problems to be solved at the level of the elements-at-risk and thus of the functional objectives given to the sediment trap, to the dimensioning of the various components (Piton et al., 2017). Managers must deal with old structures built in a different context. Former constraints regarding land availability, environment or costs explained design choices on location, shape or size, which nowadays would be different. Undertaking a detailed diagnosis of existing structures, with a particular focus on past malfunctions and adaptations, is the first step to eventually adapt structures in a world where everything changes: climate, process understanding, finance, societal expectation and risk perception.

Table 3: Main steps for the design of a sediment trap with a filtering closure check dam

N°	Step	Objective	Description
1	Study of the torrential watershed	Identification of the type of torrential phenomenon (only bedload transport, mainly bedload transport with limited driftwoods, bedload transport and driftwoods, mainly driftwood transport, debris flows) and flood scenarios (routine, project, safety-check and danger)	Historical, geomorphological, hydrological, hydro-sedimentary studies
2	Study of downstream flow conditions and assets to be protected	Definition of potential channel malfunction to be prevented	Obstruction by boulders or large wood, insufficient discharge capacity, probable high aggradation (Piton et al., 2018b)
3	Comparison of several options of protection strategies	Determining the most appropriate protection strategies	Description, investment cost including the strengthening of the channel downstream if necessary, maintenance cost (annual maintenance, dredging)
4	Analysis and comparison of criteria	Identification of the implantation site	Land, topography, accessibility, possibility of evacuating and storing the dredged material
5	Definition of the objectives assigned to the sediment trap	Assignment of the function(s), definition of its capacity and choice of the type of barrier	See §13.2.1; §13.3.3 and §13.6.1
6	Structure number and side-basin option	Choice according to objectives, finance and available space	In series, in derivation or several in series
7	Definition of the shape and size of the basin	Determination of its width, length, shape, eventual guiding channel, bottom slope as well as the probable deposition slope to estimate the height of the deposit	Field measurements, archive analysis, solid transport options available
8	Design of the barrier bottom outlet	Dimensioning of its openings in line with the structure function	According to discharge and D ₉₅ of routine and design events
9	Compliance with the type of trapping mechanism desired	Checks for consistency between the desired function and (i) the mechanical controls (boulders and driftwood), (ii) the hydraulic control (including eventual head loss associated with large wood)	Cf paragraph §13.2.3, for the project event
10	Design of the barrier spillway	Estimation of the total height, dimensioning of the overflow section and side wings	For the safety-check event.

Table 3 (continued)

11	Structural design of the barrier	Choice of the structure type (gravity, cantilever, frame) and verification of its external and internal stability	Local standard, e.g., Eurocodes (European civil engineering design standards)
12	Design of side dikes	Estimating their height including freeboard, crest slope in accordance to deposition slope, length, cross section wide enough for structural strength and foot reinforcement	For the safety-check event.
13	Design of the inlet structure	Functional design and structural dimensioning	Transfer of project and safety-check scenarios without lateral overflow
14	Prevention of long-term side effects (bed incision downstream)	Design of scour protection downstream of inlet and outlet structures	Accounting for jet scouring during overflow by safety-check event
15	Final verification of the overall project by cross control	The structure footprint must fit within the available real estate	Ensure that the estimated heights of the side dikes and barrier remain correct and not excessive, otherwise iterate

13.7 Conclusion

An inventory of the French sediment traps, located in the Alps and Pyrenees, was undertaken. A three-step approach was followed: all known open check dam were first located in a database; detailed inventory sheets were secondly filled to describe 115 structures with retention capacity > 1000 m³; and finally in-depth reanalysis were performed on a small panel of structures with interesting and rich histories. Among the 330 sediment traps first inventoried, most are in the Northern Alps. Almost all French structures have a main function of sediment transport retention and half of them have retention capacity > 1000 m³. During the second step, no malfunctions were reported for 60 % of 115 structure surveyed. For the other 40%, main identified functional malfunctions were (i) excess in trapping leading to basin too frequently filled and downstream sediment starving, (ii) lateral bypasses of the structure, (iii) structures located too upstream along the channel, and (iv) a lack of regular dredging. During the third step, a methodology with standardized forms was developed and tested allowing clustering and disentangling several failure modes of open check dams. This approach helps to exchange between specialists and field practitioners, to gather information and to improve design and maintenance processes. The comparison of new scientific knowledge with the elements resulting from this field reanalysis provides a wealth of recommendations for the design of new structures and the analysis of potential failures of existing structures.

With improved design and maintenance guidelines and innovative solutions to allow routine events to pass in compliance with the EU Water Framework Directive, it might turn out that a new generation of sediment trap will be implemented in number. For example, the choice of derivation trapping structure is a tried and tested solution both for the design of new structures and for the adaptation of existing structures (e.g. adaptation of the Manival sediment trap). It should also be noted that models can help with these innovative design: the numerical tools are a potential contribution (Kaitna et al., 2011; Gonzales de Linares et al., 2020), provided that the fields of application and limits are mastered; physical models have already been used to help the design of certain sediment traps (Couvert and Lefebvre, 1994), especially closure open check dams (Verdarel torrent in Saint-Chaffrey; Combe de Lancey torrent in Villard-Bonnot - Piton et al., 2019b), and are a very interesting way, but raise the question of the increase in the cost of study and therefore the investment cost.

Obviously, as usual in torrent control, risk assessment and structure design is and will be done in a context of major uncertainties (poor knowledge of torrential phenomena, surprising effects of structures and unexpected feedback loop or new process) and high constraints (land, environment, finance). We nonetheless hope that the experience gained for more than 50 years by the French ONF-RTM officers, and partially gathered in this chapter, can be an aid for others and followers.

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