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Design of a debris retention basin enabling sediment continuity for small events: the Combe de Lancey case study (France)

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Abstract

The Combe de Lancey stream is a relatively calm tributary of the Isère River flowing through the city of Villard-Bonnot near Grenoble (France). In 2005, a long-lasting extreme rainfall event triggered dramatic erosion processes in this 18 km² granitic catchment. A volume of 20,000 m^3 of sediment and logs deposited in the paper factory located near the fan apex. This paper focuses on the definition of a new protection system, namely a debris retention structure made of an excavated basin and an open check dam. The design is based on expert knowledge and tested byphysical small scale modelling. The particularity of this case study relies on two points: (i) its design scenarios and (ii) the structure capacity to transfer small events. Attention was paid to define several 100-year return period events used as "design events" for which the structure must have its best effectiveness. Extreme events with higher return periods called "safety check events", for which the structure must still withstand the event without failure but with acceptable marginal damages, were also modeled. The definition of the scenarios is described in the paper. Secondly, the debris retention basin should have the capacity to transfer small debris floods without trapping sediment in order to prevent downstream incision and heavy maintenance costs. It must however trap nearly totally the sediment and large woods that are erratically supplied by the catchment during extreme events. Classical debris retention basins are usually not able to achieve such a dual objective. Here, two concepts developed in past works, namely a guiding channel and a hybrid open check dam with mechanical – hydraulic control were successfully tested. The paper presents the design and testing procedure of this case study exemplifying the next generation of debris retention structures.

Keywords: debris flood, hazard scenario, open check dam, guiding channel

1. Introduction

Steep mountain streams erratically experience debris-flows and debris-flood events releasing massive amounts of sediment and large woods on fans. The municipality of Villard-Bonnot is partially built on the Ruisseau de la Combe de Lancey alluvial fan and aims at removing here a closed paper factory to create new residential areas. Before doing so, the French state requested a torrential hazard mitigation plan to protect the whole fan. Past studies demonstrated that a debris retention basin was part of the best option (SOGREAH 2010). The best location to build it is at the slope break between the upstream gorges and the alluvial fan (Fig. 1). Indeed, massive deposition was observed in the last extreme event at this location.

Designing a debris retention basin in a city center deserved a detailed analysis which has been performed using expert assessment along with numerical and small scale physical modelling. This case study had two particular challenges so far poorly addressed in the literature and worthy of publication: (i) determination of the debris-flood multiple scenarios and (ii) solutions to enable sediment transport in normal conditions while trapping all gravels and large woods for events overloading the quite low channel capacity. This paper synthetizes these points after a short presentation of the catchment and before to briefly describe the structure behavior in physical small scale model subjected to various scenarios. All details may be found in the technical report by ARTELIA and IRSTEA (2018).

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2. Catchment short presentation

The Ruisseau de la Combe de Lancey is a steep stream flowing from a 18 km² catchment in the Belledonne mountain range, north-east to Grenoble. Its confluence with the Isère River is located on the Villard-Bonnot municipality that occupies its alluvial fan. The torrent passes through four geomorphic units along its path (Fig. 1a & b). The steep headwaters experience erratic debris-flow activity. Along the 6 km of 12%-steep mid-mountain range, the torrent has a very stable, about 4 m wide steep-pool pattern with a wider paleo-bed. A very steep gorge with a bedrock and cascade bed connects the mid-range with the alluvial fan. The fan is almost entirely occupied by a huge 19th century paper factory now closed, the village center, a regional road and the railway to Italy (Fig. 1c). The final torrent section is 1.5% steep before its confluence with the Isère River. It is worth being stressed that where the river channel crosses a deep ditch dug to drain the Isère floodplain a long time ago (Fig. 1c), the torrent has only the capacity to carry 7 m^3/s, so that any additional discharge supplied by the catchment is lost in the drainage ditch.

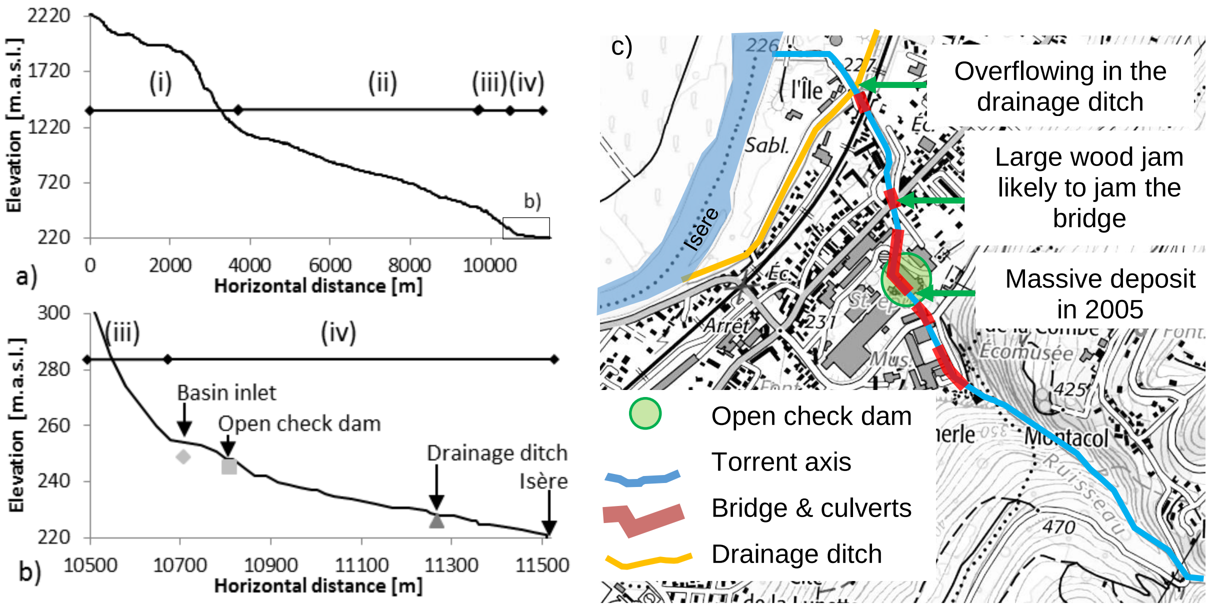

Fig. 1: a) full longitudinal profile of the Combe de Lancey torrent, split in four sections (i) headwater, debris-flow reaches, (ii) mid-range 12%-steep section, (iii) 28%-steep final gorges and (iv) alluvial fan; b) zoom on the fan section with location of the debris deposition basin, drainage ditch and confluence with the Isère River; c) map of final gorge and alluvial fan areas, location of bottleneck sections with deposition, jamming and overflowing issues (©IGN BD Alti 25m and Scan25).

The granitic geology of the catchment makes primary sediment production quite low; consequently, bedload sediment transport is supply-limited under normal conditions. Large sediment supplied to the fan is in any case limited by the mid-mountain range 12%-slope, except in the case of landslide in the final gorges which has been considered possible but very improbable and consequently not studied further in detail.

On Aug. 21st and 22nd, 2005, a long lasting extreme rainfall event hit the Belledonne mountain range (IRMA 2006). Most torrents with sources located close to the summits experienced flood events with high intensity lasting at least 24 h, triggering massive geomorphic adjustments and debris releases on fans. The Combe de Lancey experienced debris flows in the headwaters and debris floods further downstream. Bridge clogging and bed widening in the mid-range occurred and 20,000 m^3 of gravels deposited under and around the paper factory at the slope break between fan and gorges. Water peak discharges were not extreme (Q~22 m^3/s, return period ~ 30 yrs, SOGREAH 2010) but the high flows lasted about 24 h, much longer than under usual thunderstorm conditions. The multivariate nature of this event, i.e., peak flows, duration, sediment transport, large wood recruitment or resulting damages, makes a direct estimation of a return period difficult but it can certainly be considered as exceptional. If considering simply damages, the historical records let us think that the return period of such events is closer to centuries than to decades. Not all details could be provided here for the sake of conciseness. The paper rather aims at conceptually explaining the coupled historical – geomorphic – physical appraisal used to fine-tune the structure to the torrent.

3. Design scenarios for debris-flood events

3.1. Event status in design scenarios

Debris retention basins fundamentally aim at partially changing the sediment cascade processes but should optimally (i) only influence events likely to create hazardous problems, (ii) fully cope with a certain range and variability of events and (iii) not aggravate hazards when overloaded beyond their capacities. Several event magnitudes were consequently studied. (Fig. 2 and Table 1):

- As mentioned above, the torrent has the capacity to convey down to the Isère River only discharges up to 7 m^3/s, i.e., about the annual peak flows. Trapping the bedload transport occurring below those conditions would increase cleanout costs for the structure, trigger sediment starvation downstream and should therefore be prevented with a suitable design. Several short runs on the physical small scale model with low sediment supply were tested to verify this point and are hereafter referred to as *"routine events"*.
- The structure should be able to cope with a similar event than the one experienced in 2005, which is assumed to have a return period of damages of about 100 years, these damage being mostly related to the volume of sediment transport. Assuming that sediment transport is mostly related to the hydrograph (see below for a discussion on this point), one must consider that a 1:100 years return period event could also have other features, e.g., a shorter duration but higher peak discharge. Two events with exceedance probability of about 1:100 years were tested and are hereafter referred to as *"project design events"*. Under these various harsh conditions, the structure must fully protect the area, i.e., with a certain safety factor taken as a 1 m-high freeboard on the flow level.
- A protection structure should not fail and aggravate the hazards even under a certain range of events with magnitudes higher than these project design events or more rare events with extraordinary features, e.g., massive armor breaking in the stable step-pool systems or cascading hazards of landslide and strong thunderstorm triggering an abnormally sediment-laden flood. Such events were tested as *"safety check events"* to control the structure robustness and reliability. For these events, a null freeboard is considered acceptable but full structure failures are not. They aim at understanding possible failure modes and at raising stakeholder awareness that structures protect up to a certain limit.

Table 1: Synthesis of event scenarios

Name	Event status	Sediment main source	Return period [yr]	Peak discharge [m^3/s]	Event* duration [h]	Solid volume [m^3]	Structure objective for this event
Small events	*Routine events*	Armored torrent bed	<<10	3-7	3-7	<<1,000	Sediment transport transfer downstream, no trapping
Type 2005	*Project event*	Debris flows in the headwaters	~100	22	30	20,000	Maximum effectiveness with 1m freeboard and without large woods releases to the downstream channel
Long thunderstorm	*Project event*	Debris flows in the headwaters	~100	35	18	20,000	
Armor breaking	*Safety check*	Large scale armor breaking	>100	35	18	20,000	Observation of potential failure modes for safety check: the structure should not aggravate the hazards but may be overloaded and not able to cope with such events. Freeboard may be null
Short & Hyper-concentrated	*Safety check*	Landslides or massive bank erosion in the catchment inter range	>100	22	14	20,000	
Volume overloading	*Safety check*	Larges debris flows in the headwaters	>>100	35	36	40,000	
Debris flows	*Extreme*	Landslide in the steep gorges just above the fan	>>100	?	?	?	Considered too unlikely to be studied.

* Event duration: full hydrograph duration, assumed to be four times longer than the rainfall and two times longer than the flood high stages as displayed in Fig. 2.

3.2. Computation of event hydrographs

The first step was to reconstruct the 2005 event. Analyzing historical data, crisis management reports, *ex-post* technical reports and rainfall data, a hydrograph has been proposed to model the event with the following features:

peak discharge Q_p=22 m^3/s, high flow stage duration, i.e., with $Q>Q_p/2$, t=10 h, a full duration of 36 h and a water volume of 760,000 m^3.

The other ~ 1:100 years flood event was considered to have a hydrograph with maximum value Q_p=35 m^3/s (SOGREAH 2010), a high flow stage shorter duration t_1=5 h, a full duration of 18 h and a volume of 560,000 m^3 of water as a response to a 5 h rainfall event.

To the best of authors' knowledge, recommendations based on the determination of discharges – durations, of given exceedance probability, in the context of debris flood-prone ungauged mountain streams – have never been tried or tested. To estimate longer hydrologic events of similar exceedance probabilities, a straightforward technique has been used: assuming that peak discharges are proportional to the rainfall intensities - the so-called "rational method" in discharge estimation - one can express peak discharges as a power equation on time:

$$Q_p(T,t) = \frac{C(T).A.I(T,t)}{3.6} = \frac{C(T).A.a_T.t^{1-b_T}}{3.6} \qquad \Leftrightarrow \qquad \frac{Q_p(T,t_1)}{Q_p(T,t_2)} = \left(\frac{t_1}{t_2}\right)^{1-b_T} \qquad (1)$$

with event time return T [years]; peak discharge Q_p [m^3/s]; runoff coefficient C [-]; rainfall intensity I [mm/h], catchment area A [km²], rainfall intensity-duration coefficients a_T [mm/h] and b_T [-], and rainfall durations t, t_1 and t_2 [h]. Fig. 2 displays the peak discharge reduction against rainfall duration using b_T=0.37, mean value of the frequency-intensity-duration curves measured at the rain gauges located on or near the Belledonne massif (Allevard, Fond de France, Saint Martin d'Hères, according to Djerboua 2011). The longer project design event, corresponding to the 2005 disaster, falls in the ±20% uncertainty range around this 1:100 year exceedance probability domain (Fig. 2, light blue area). The same method has been used to estimate other exceedance probability domains based on discharge knowledge for 1:10 years and extrapolating using daily rainfall extreme values and discharge-rainfall relationships according to Carré and Fretti (2010) for 1:1,000 years.

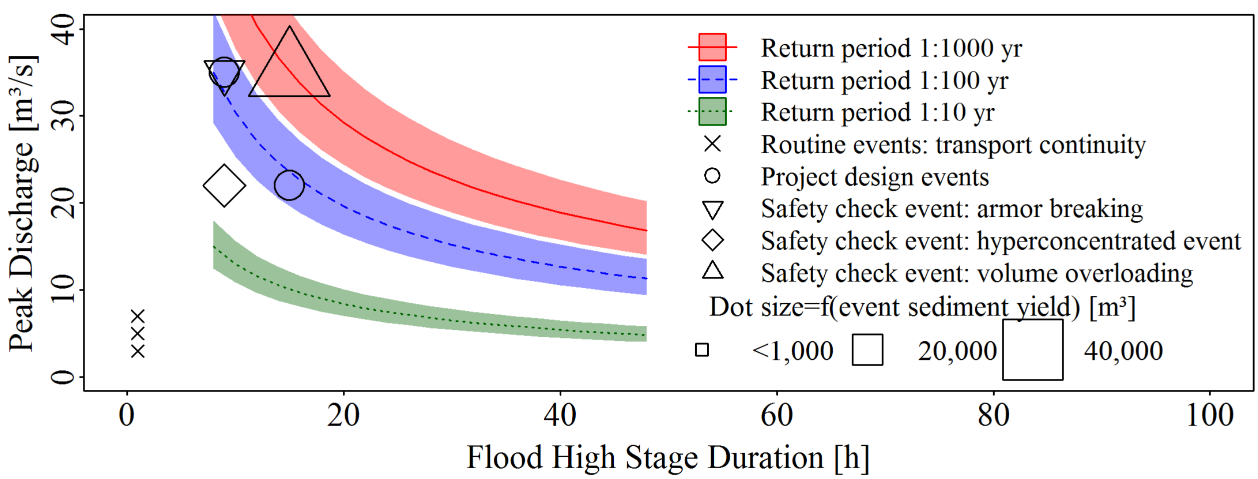

Fig. 2: Theoretical peak discharge – flood high stage duration for both routine, project and safety check events; exceedance probabilities of event magnitudes are based on rainfall intensity and peak discharge – rainfall relationships; sediment yields are computed with a bedload transport formula.

3.3. Computation of sediment yield and geomorphic scenarios

Bedload transport has been computed in a second step according to the "travelling bedload" framework specifically suitable for heavily armored bed experiencing colluvial sediment inputs, e.g., debris flows and landslides (Piton and Recking 2017). All the fan being urbanized and mostly covered, no alluvial material could be found near the structure location to assess the fan apex grain size distribution representative of debris-flood events. Measurements were thus realized upstream in the mid-mountain range (D_{84}=332 mm) and downstream on the fan distal part close to the Isère confluence (D_{84}=98 mm). Based on evidences of 2005's disaster pictures, debris-flood events were assumed to supply grain sizes finer than the first sample but coarser than the latter. Project design events were tested with a mixture of 40% of the coarse gorge sample and 60% of the fine fan one. It has additionally been observed that cobbles of approximately 400 mm of diameter tended to deposit in the fan channel and hardly to be transported until the Isère confluence.

Using this grain sizes with the aforementioned 2005's hydrograph and the mid-mountain range 12% slope resulted in a sediment yield estimation of 58,000 m^3, nearly three times the 20,000 m^3 observed in 2005. This is consistent with the supply-limited state observed in normal condition: only rare triggering of massive debris flows in the headwaters can supply the material to generate debris floods. As often done in practice, the slope has been artificially lowered to 6.8% in order to model this supply-limitation and obtain the 20,000 m^3 transport under the reconstructed hydrology.

Several hypotheses had to be done on hydrology and sediment sizes and availability as described above. Scenarios testing the occurrence of events different than expected were used as safety check events (Fig. 2, Table 1):

- A safety check test was performed using coarser grain sizes corresponding to 60% of the gorge sample and only 40% of the fan sample. This event is assumed to correspond to a large scale armor breaking event. This test aimed at verifying the structure capacity to cope with the supply of sediment coarser than usual.
- Another possible geomorphic scenario is the occurrence of landslides and mass wasting processes into the torrent bed and the occurrence of a flood event of moderate magnitude, e.g., exceedance probability 30 years, before that channel cleaning with earth moving machinery could be performed. Such an event would trigger sediment laden flows loaded at full transport capacity, i.e., with the geometrical slope of 12%. This test aimed at verifying the structure capacity to cope with the supply of sediment with a solid concentration much higher than usual.
- Performing hydrology studies of ungauged high mountain catchments is highly uncertain. In addition to the two project design events which vary mostly in term of hydrograph, another safety check event aimed at testing how the structure respond to both a long (38 h) and intense event (Q_p=35 m^3/s) supplying 40,000 m^3 of sediment, thus strongly overloading the debris basin volume capacity. Its hydrological exceedance probability is assumed to be about 1:1,000 years (Fig. 2).

3.4. Large wood recruitment

In addition to sediment and water, extreme debris-flood events recruit large woods, i.e., logs longer than 1 m and diameter higher than 0.1 m, on banks and from mass wasting processes. During the 2005 disaster, a cumulated volume of 600 m^3 of large wood jams was measured in the catchment (ONF-RTM 2005). This value is close to the lower envelope of values estimated from empirical formulas (400 m^3-3,000 m^3) as reviewed in Piton and Recking (2016a). Large wood jams in retention basins increase obstruction ratio and trapping performances but are also likely to be released aggravating downstream hazards. They should consequently be considered cautiously during the design procedure (Bezzola et al. 2004). Based on historical evidences and observations of large wood pieces in the final gorges, a total absence of large wood pieces was considered really unlikely. However, in order to prevent an overestimation of trapping capacity, a relatively small volume of 100 m^3 of large wood pieces were introduced during the raising limb of the hydrograph during all events tested in the laboratory. Close attention was paid to observe large wood accumulation and abrupt releases by overflowing possibly generating jamming problems further downstream (Fig. 1).

4. Debris retention basin design: basic and optimized

The basin has a diamond shape adjusted to the area available in the current and future urban fabric. It is roughly 100 m wide and long. The design is inspired by the state-of-the-art reviewed by Piton and Recking (2016a, 2016b) and by Schwindt et al. (2017, 2018) for the adaptations to enable sediment transport continuity during routine events while fully trapping sediment transport for larger events.

- The basin bottom slope has been chosen at precisely 1.5%, i.e., value of the bottleneck downstream reach, from the drainage ditch to the Isère River (Fig. 1). In essence, the structure should be able to transfer precisely the amount of sediment that the most constrained part of the whole downstream torrent system is able to export. This bottleneck reach has a hydraulic capacity of 7 m^3/s. A guiding of channel of precisely the same capacity was dug in the basin to enable the continuity: the slope is not sufficient to transfer the sediment load if flows spread in the basin, flows must also be laterally constrained to keep their transport capacity (Piton et al. 2018a).
- Designing an open check dam able to transfer all sediment transport for routine events and trapping nearly all higher sediment supplies was an unresolved challenge until recently. The recent works by Schwindt et al. (2017) and Roth et al. (2018) provided clear recommendations to do so with so-called "hybrid" open check dams. Such

structures have a bottom outlet that takes advantage of (i) a orifice hydraulic functioning to rapidly increase head losses and trapping capacity when discharges overpass the guiding channel capacity, along with (ii) a preceding grill with bottom clearance that prevent self-flushing during flow recession. The grill bottom clearance was 0.4 m high, the space between bars was 0.2 m and the bottom orifice was 4 m wide and 0.5 m high in the first option, adjusted to 0.8 m after preliminary tests (Fig. 3).

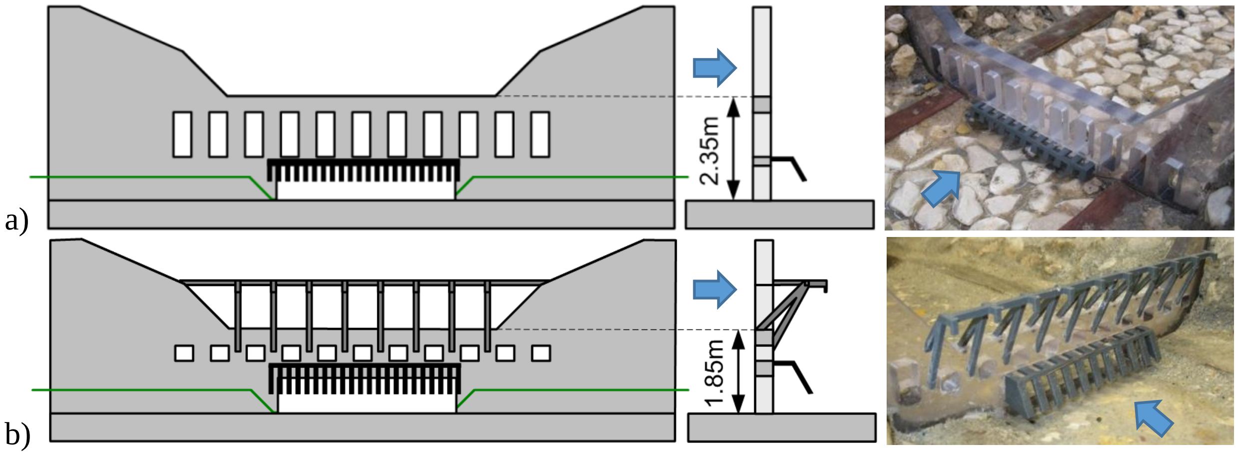

Fig. 3: a) Basic and b) optimized versions of the open check dam: upstream and left side views at prototype scale and pictures of the 1:40 scaled physical model. Blue arrows display the flow direction. The bottom slot was equipped with an inclined grill according to the hybrid mechanical-hydraulic controlled described by Schwindt et al. (2017); optimization consisted in increasing the bottom slot height of 0.3 m, lowering the spillway level by 0.5 m and adding a rack on the spillway to retain large woods in the basin

Above this outlet dedicated to the routine event management, eleven vertical slits were added to enable flows from routine events up to project design events to pass through the dam. They were 1.0 m high, adjusted to 0.35 m in a second round and 0.4 m wide. The slits' width was narrow enough to rely on their clogging by the cobbles of the same size observed in the channel. Additionally empirical evidences from other catchments let us think that mixtures of large wood pieces and even finer gravels will very likely lead to the clogging of the whole dam for heavy solid supply.

Finally a typical 6 m-wide trapezoidal spillway was added at a height of 2.35 m above the river bed, decreased to 1.85 m after optimization. This crest feature should prevent structure by-passing and guide extreme event flows or design event flows when outlets' clogging occurs. After a few tests, the following observation made clear some slight optimization needs as illustrated by difference between Fig. 3a & b:

- The 4 m-wide, 0.5 m-high bottom slot and inclined grill triggered a head loss a bit higher than expected likely to trap sediment for discharge in the range 4-7 m^3/s. The bottom slot height was consequently increased to 0.8 m.
- The structure was able to trap all of the project design events' sediment supplies; some room even remained in the basin distal part due to the quite steep deposits (see later). Lowering the water level would enable the deposit front to prograde faster in the basin and optimize its filling. The spillway level strongly controlling the water level, the structure crest had consequently been lowered by 0.5 m, thus lowering too the vertical slit height.
- Large wood accumulated against the open check dam, clogged the bottom slot and some slits, thus increased head losses and water levels. No abrupt and massive release of large woods was observed for discharges up to 28 m^3/s, while nearly full large wood overtopping was observed for discharge approaching 34 m^3/s. A rack dedicated to retain large woods in the basin was added on the spillway crest to prevent it.

5. Short description of structure behavior on the physical small scale under various event scenarios

The optimization proved to have satisfactory results: (i) flows up to 7 m^3/s were only marginally influenced by the basin and new dam and (ii) large woods were mostly retained upstream of the rack, only a few pieces passed in uncongested transport. The prevention of wood release maintained however higher head losses and the basin filling did not significantly change between the basic and the optimized designs. Safety check events were then tested to check failure modes and structure functioning robustness.

In addition to those empirical observations, classic measurements methods were used on the small scale model: photogrammetric analysis and surface velocity measurements by image analysis (Piton et al. 2018b). All events followed similar geomorphic trajectories although with various celerity and slight random variations. In essence: some bedload transport occurred in the guiding channel, however most of the supplies massively deposited near the basin inlet as soon as water discharge overpassed the 7 m^3/s threshold. A small fan-like pattern grew and progressively prograded in the basin, the active channels wandered, split and merged on the depositional form. Since basin bottom slope was low and head losses rapidly grew, most of the basin was flooded and deposition actually occurred under a delta shape rather than a pure alluvial fan shape. The delta eventually reached the open check dam and large wood accumulation only occurred near the end of the events. The basin thus trapped all of the sediment supply, except for the volume overloading event. During this particular event, the bedload transport continuity was recovered near half of the run and 13,000 m^3 out of the 40,000 m^3 supplied were transferred in the channel downstream. The basin was thus capable to store 27,000 m^3 at most, i.e., with null freeboard.

Maximum deposit elevations were measured to design the lateral embankments (Fig. 4). The project design event deposits plus the 1 m freeboard, as well as the safety check events (volume overloading and hyperconcentrated) with null freeboard, were measured above the ground level on a length of about 50 m from the basin inlet. Embankments suitably protected from erosion are required in this section. Conversely the simple excavation of the current ground is sufficient to contain the flows and depositions further downstream. Depositions slopes are relatively constant between events, around 5-6%, except for the hyperconcentrated and armor breaking events, which naturally resulted in steeper deposits with slopes around 7-8%.

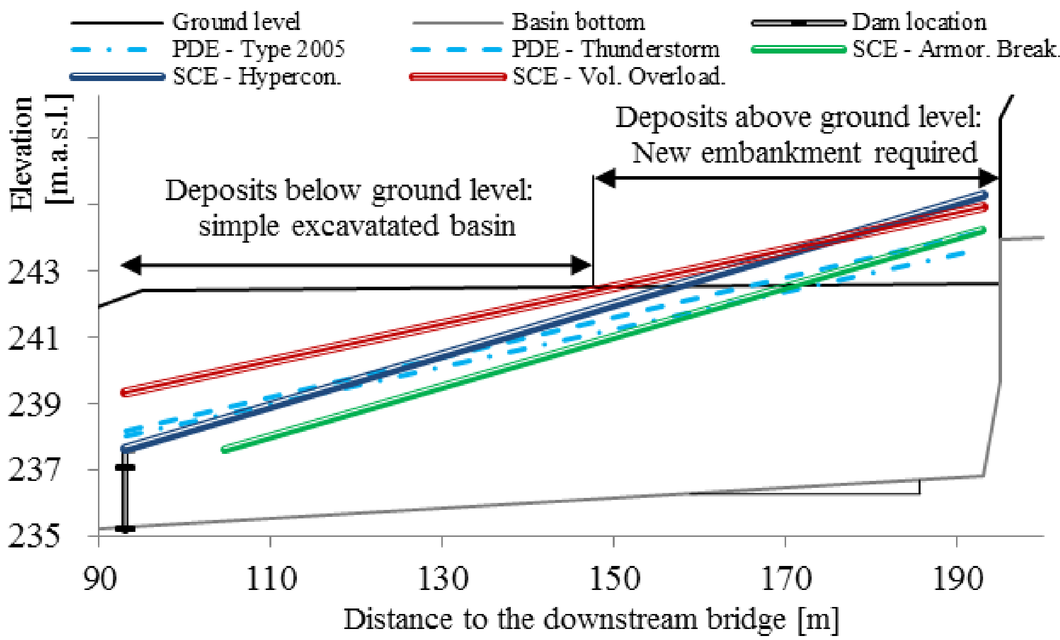

Fig. 4: Longitudinal synthetic profiles of ground level, i.e., current terrain in the area, basin bottom level, i.e., excavation to be performed to dig the basin, and deposit maximum elevations for the various scenarios: either project design events (PDE) or safety check events (SCE). Both project design events have very similar deposit maxima despite their different dynamics; both the hyperconcentrated and the volume overloading safety check events were necessary to determine the deposit maxima for extreme events enabling to check the embankment length.

6. Discussion and conclusion

Debris retention basins are complex structures whose filling and responses to the natural variety of processes have been seldom directly observed (Piton et al. 2018a). The deposition process complexity (Piton and Recking 2016a) and interactions between structures and large woods (Piton and Recking 2016b) are consequently not fully understood. To the best of the authors' knowledge, numerical models are not yet considered to be fully reliable tools to model debris-flood events, i.e., gravel, water and large wood mixtures flowing on slope of 5-15%. Small scale physical modelling was and is still a powerful tool to perform comprehensive analysis of such processes. But performing each run is costly in labor force and time, typical case-studies can consequently afford only a handful of runs. Ensuring the necessary representativeness of those runs and not missing a likely surprising behavior resulting in the structure failure is thus of utmost importance. Testing the great variability of torrential flows observed in Nature by clearly highlighting the hydrologic and geomorphic scenarios likely to occur is thus a key preliminary study of any expensive small-scale physical model campaign.

Based on a recent case study of the Ruisseau de la Combe de Lancey in France, this paper shortly describes how the authors chose to deal with historical, geomorphic and physical data and methods to fine tune a debris retention basin. Three types of events were modeled:

- *Routine events* enabled to test and optimize the design so that small magnitude events, not threatening the village, could be transferred with marginal trapping to prevent maintenance effort and environmental degradation.
- *Project design events*, of various peak discharges and durations but globally having a ~ 1:100 years return period, enabled to verify the structure capacity to cope with such events with a reasonable freeboard.
- *Safety check events*, less probable though without specified exceedance probability due to the lack of data, enabled to test a greater variability of hydrological and geomorphic events and to make sure that no failure mode would appear for those magnitudes that remain possible although quite rare.

We hope that this example of applied research will help practitioners in other case studies or researchers in connecting scientific challenges in hydrology, sediment transport and extreme value theory with the challenges posed by the application data-scarce context.

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