2 Materials and methods

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The methodology consists of four main steps (Fig. 1): (1) literature review and selection of case studies of natural and urbanized alluvial fans from different climatic regions based on landform characteristics, (2) analysis of key factors contributing to both failure and non-failure (success) of the flood prevention measures, (3) investigation of the hydro-sedimentary dynamics of natural (non-urbanized) active alluvial fans to derive nature-based solutions for safer urbanization, and (4) development of a physical laboratory model to test these concepts, incorporating a nature-based design for sustainable urban development on alluvial fans.

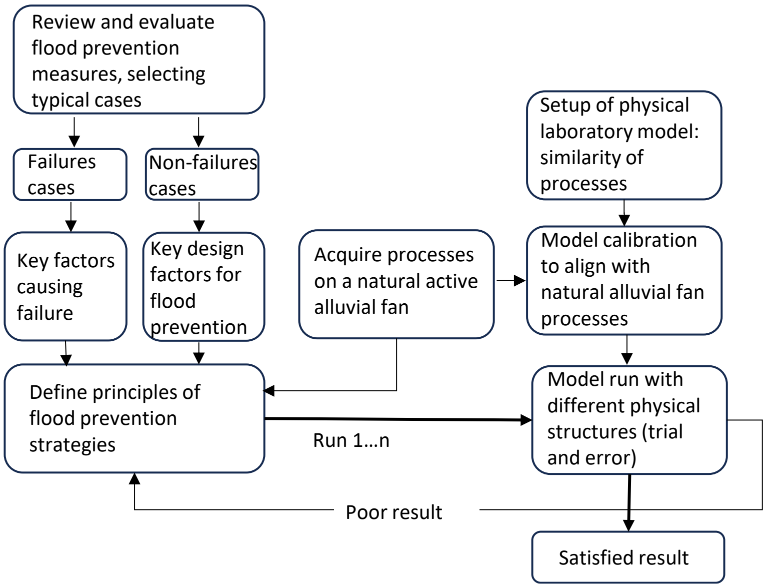

Figure 1: A schematic diagram of the methodology

The literature review (Step 1) was conducted to select case studies of large flooding in urbanized and natural alluvial fans. Case studies were selected based on four key criteria: (i) severity of the event, (ii) thorough documentation, (iii) availability of sufficient data for re-evaluation, and (iv) diversity of the cases in terms of causes, geographic locations and contexts. A preliminary analysis has identified similarities in processes across geographic domains, particularly at the fan head and mid-fan, in relation to flood hazards.

For urbanized alluvial fans (Step 2), the reliability of flood control measures -comparing failure and non-failure cases- was analyzed to identify their limitations and the key factors contributing to degradation and collapse. This analysis focused on four case studies, including: (i) Caraballeda flood: Wieczorek et al., 2001; Larsen and Wieczorek, 2006; Salcedo, 2000; Lopez and Courtel, 2008; (ii) Biescas flood: García-Ruiz et al., 1996; Benito et al., 1998; Alcoverro et al., 1999; (iii) Oak Creek alluvial fan: Wagner et al., 2012; GE images, July 2007–June 2009; and (iv) Wadi Yutum: Schick, 1971; Farhan and Anbar, 2014; Bany-Mustafa, 2016; Eom et al., 2011; Grodek, 2024. GE image Dec. 2004. The cases analyzed helped to clarify the benefits of urban design in reducing the impact of flooding. In particular, the Eilat City Alluvial Fan Field Laboratory, established in 1966 (Table 1, section 5.1), provided a continuously monitoring urban design, geomorphology, climate and hydrology (e.g., Sharon, 1972; Schick and Lekach, 1993; Lekach and Enzel, 2021). The flood hazard of the city of Eilat City is summarized by Grodek et al. (2000) and Grodek (2024).

To illustrate the degradation of sediment control measures over time (e.g., check dams), we present Figure 10, comparing the design factor of safety (FS) with the actual FS. The Pyrenees serve as an example for this analysis, specifically the Biescas case (discussed in Section 3.2):

$$FS = \frac{\text{stability force}}{driving\ forces}$$

The stability force refers to the structure's strength (e.g., building materials and structural integrity), while the driving forces include factors such as structural degradation, aging, sedimentation pressure, water content, bank erosion, seepage, piping, and the severity of the expected events. An FS < 1 marks the point at which the structure is at risk of failure. Given the large number of parameters involved, physical calculations are complex and unreliable. Therefore, we demonstrate FS using the modified Gompertz-Makeham law of mortality to model its progression over time:

$$FS(t) = A - Be^{\gamma t}$$

A represents the FS engineering design (1.5), B is a scaling constant for the age-dependent term (design: 0.0005 and actual: 0.03) and γ is the exponential structural degradation over time (design: 0.069 and actual: 0.05).

For the sedimentation rate of a check dam, $V_s(t)$, we use an empirical model for an object experiencing exponential growth towards a certain limit (calibrated based on sections 3.1 and 3.2):

$$V_s(t) = V_0\,(1 - e^{-kt})$$

where V_0 is the maximum check dam capacity (10,000 m^3), and k is a constant that represent the rate of change (0.07).

The spatial distribution of landforms and surface processes (Step 3), including debris flows, in-channel flows, and unconfined flows, was analyzed on an archetypal natural alluvial fan: Turkey Flat (Section 5.2; Table 1). This case study represents a pristine alluvial fan environment where surface processes and hydro-morphological parameters can be accurately quantified. Two distinct regimes exist within this natural fan, each characterized by different processes: the fan head and the main fan area. Within these morphological domains, the spatial distribution of landforms and surface processes -including sediment transport and deposition, fluvial processes, debris flows, in-channel flows, and unconfined flows—have been thoroughly examined (Section 5.2). This analysis provides important insights into the hydro-sedimentary dynamics that shape different sections of the fan and offers valuable guidance for developing nature-based solutions to support safer urbanization.

Finally, a laboratory physical analogue model was applied to test various types of flood prevention measures (Hooke, 1968; Schumm et al., 1987; Peakall et al., 1996; Davies et al., 2003; Clarke et al., 2010; Green, 2014). The setup consists of a feeding channel, fan table, water supply, sand/gravel and measuring devices (see Appendix A1). Multiple tests were conducted to optimize the feeding canal for continuous sediment flow. The water flow rate was set at 0.4 l/min to cover 25% of the fan area, increasing to 2.0 l/min for full coverage, corresponding to sediment concentrations of 25–30% by weight (100–600 g/min). The apparatus was first calibrated to replicate the fluvial processes of the Turkey Flat alluvial fan (Fig. 8; Section 5.2), including forms, dynamics, behavior, and geometries (similarity of processes). Subsequently, different control measures were tested for their functionality (detailed model setup in Appendix A).

Table 1: The examined alluvial fans - basic parameter.

Stream	Basin Area km^2	Basin slope %	fan area, km^2	Fan slope %	Debris volume Mm3	Basin/fan ratio	Melton * R	Location
3.1 Caraballeda-San Julian (Ven.)	21.3	23	4.4	11–7	2	4.8	0.46	+10.61°N +66.85°W
3.2 Biescas (Spain)	18.3	20–6	0.73	7.5	0.17	25.1	0.28	+42.61°N +0.33°W
3.3 Oak Creek (US)	32.5	9	13.9	8–3	1.5	2.3	0..37	+36.85°N -118.24°W
3.4 Aqaba – W. Yutum (Jordan)	1,720	1.7	47	3.4–1.2		37	0.05	+29.69°N +35.02°E
5.1 Eilat, N. Mekorot (Israel)	0.8	5.9	1.8	7–3	0.0009	0.4	0.10	+29.56°N +34.94°E
5.2 Jordan Stream (NZ)	12.3	20–4.3	5.1	4.3		2.7	0.41	-43.01°S +171.55°E

*Melton R likelihood for debris flows, 0.35–2.0 (typically >0.7) and 0.07<R<0.7 is the range for fluvial flow processes (Melton, 1965).