Okanagan Alluvial Fan Hydrology: A Primer

Alluvial Fan Hydrology Committee (AFHC)

on behalf of the

Okanagan Water Stewardship Council

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Executive Summary

This Primer is intended to provide a concise summary of what alluvial fans are, the types found in the Okanagan, and some of the management concerns related to their existence on the natural landscape as it intersects with the expanding human foot print. Some actionable recommendations are provided.

Alluvial fans are depositional features located wherever water flowing in a channel loses confinement, typically because the channel is no longer constrained by valley side-slopes. The classic alluvial fan, of which there are many prime examples found throughout the Okanagan Basin, has a distinct fan-like geometry with a narrow apex at the transition from steep, mountainous terrain onto a flat valley floor. The main feeder stream flowing in the confined channel above the fan apex encounters the flatter terrain below and splays out radially in a system of distributary channels across the fan surface. The active channels carry water and sediment, sometimes in the form of debris floods and debris flows, which leave distinctive topographic and sedimentologic signatures on and within the fan deposits. There are also many alluvial fans across the Okanagan Basin that do not adopt the classic shape and are, instead, found at mid to high elevations where coarse-grained deposits were laid down in reaches where the channel widens and accumulates. Such mid to high elevation fans are often located at tributary junctions but are difficult to identify using aerial photographs because of thick, forested vegetation cover and because of their limited spatial extent.

Valley-bottom fans and mid to high elevation fans are important in terms of: (a) their influence on the water balance because of surface-groundwater exchanges; (b) consequent implications for water supply and environmental flow needs; (c) the potential hazards they pose to downstream infrastructure; and (d) the need to manage landscapes with alluvial fans in ways that avoid risk to human population and development as a consequence of human modification to the natural conditions that created and evolved the alluvial fan (e.g., logging road cuts; aquifer dewatering; urban development).

Fans are often seen as desirable locations for human occupation and exploitation, with sediments amenable to quarrying, trees that are readily harvested, and panoramic views of the surrounding valley. However, they should be viewed circumspectly as places where large fluxes of energy and matter (water and sediment) are concentrated. The complex history, internal structure, and modern processes on fans make it difficult to predict what the specific ramifications of a particular alteration, occupation or development of a fan might be Climate change will increase pressures on water resources and habitat on fans.

Hazards on alluvial fans include floods, debris flows, the lateral migration of main and side stream channels, erosion, and the potential for artesian groundwater conditions near the toe of fans. These hazards only become risks to people when human activities are located on fans. Risks to human infrastructure are best avoided by limiting human use of fans. Risks are always present for natural ecosystems and in-stream habitats, and these risks can be increased by human activities in the upper watersheds or on the fans themselves.

This report recommends: increasing awareness of alluvial fans, their hazards, risks and challenges among stakeholders; collating existing reports to create a common hazard/risk matrix for the Okanagan; encourage the use of new analytical tools such as advanced geochemical tracing methods, computer modeling of groundwater flow in fans, and detailed terrain data from recently collected LiDAR missions; and share data among Okanagan regions and improve monitoring of streamflow and climate. In particular, future projects should work towards developing an inventory of Okanagan alluvial fans, and coupling that to a risk-ranking scheme for fans in order to prioritize future detailed studies. These initiatives should be accompanied by efforts to engage senior levels of government for assistance with funding and outreach activities.

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AFHC Members

Bernard Bauer (Co-Chair), University of British Columbia Okanagan
Craig Nichol (Co-Chair), University of British Columbia Okanagan
Lorne Davies, Geostream Environmental Consulting
Fes de Scally, University of British Columbia Okanagan
Drew Lejbak, Associated Environmental Consultants Inc.
Michael Milne, M.J. Milne and Associates Ltd.
Natasha Neumann, BC Ministry of Forests
Nicole Pyett, BC Ministry of Forests
Sheena Spencer, BC Ministry of Forests
Chani Welch, Okanagan Nation Alliance

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INTRODUCTION

Alluvial fans are depositional features commonly found in mountainous terrain that are formed by sedimentary processes associated with flowing water (i.e., 'alluvial' processes). These distinctively fan-shaped deposits are created when creeks and streams confined within narrow, steeply-sloping valleys or canyons transition to an open area of gentle gradient (Figure 1). Here, the flow is no longer constrained by valley walls and therefore spreads laterally (Harvey 2018). As a consequence, the flow begins to slow down and the sediment-carrying capacity of the water diminishes. Much of the material being transported by the flow will be deposited, initially at the apex or 'head' of the fan, but also progressively farther along the fan surface as the entire feature grows longer and wider.

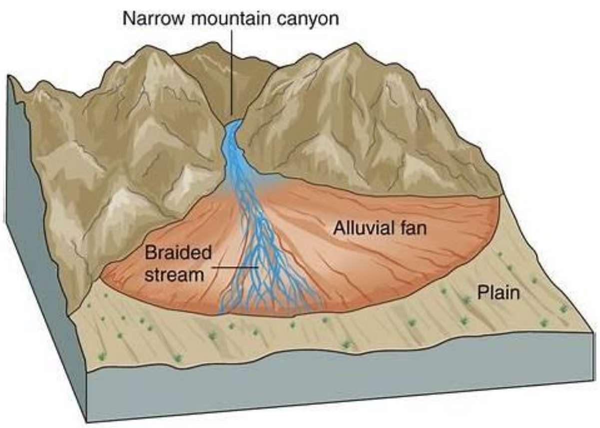

Figure 1: Classic alluvial fan geometry (from https://www3.nd.edu/~cneal/PlanetEarth/Lab-Deserts/Depositional.html)

When looking down on an alluvial fan from high above (i.e., planform view), the overall shape of the deposit will have a crudely triangular fan-like shape with the distal margins or 'toe' region taking on an arcuate or semi-circular geometry. However, in cross-section from the apex to the toe, fans look more like a segment of a cone with a ground surface that has either a straight slope or slightly concave upwards slope – i.e., steeper at the apex, and flatter at the toe. The fan head is roughly the location where there is a transition from an erosional environment upstream to a depositional environment downstream.

Much of the early literature on alluvial fans was based on examples of landform features found in arid and semi-arid environments (e.g., Eckis 1928; Blissenbach 1954; Denny 1965; Melton 1965) where vegetation cover does not obscure the morphometry (overall three-dimensional shape) of the fan and where ephemeral (periodically or seasonally flowing) streams in entrenched river beds and canyons splay out onto broad, shallow valleys or playas. There are many other topographical configurations that might lead to the formation of alluvial fans, but they all involve a break in slope from steep stream reaches upslope to shallower gradients where the depositional landform accumulates.

There is an extensive literature on the effects of plate tectonic movements and changing base level (the lowest elevation to which a river flows) on fan development (e.g., DeCelles et al. 1991; Fernández et al. 1993; Jansson et al. 1993; Viseras et al. 2003), especially the prevalence of fans at major fault lines where block uplift has occurred (e.g., horst and graben topography, mountain fronts). However, such tectonic effects on alluvial fan development are not particularly relevant to the Okanagan Basin context where there has been relatively little vertical tectonic displacement of the valley's underlying bedrock, and therefore this issue is not discussed further as a precondition for fan formation[1].

In the Okanagan Basin, alluvial fan-like features are found at all elevations and in a range of sizes from metre-scale deposits at high and mid elevations to very large fan-deltas (e.g., Fintry) and deltaic landforms (e.g., mouth of Mission Creek) at valley bottoms that are more than a kilometre across. Given the variety of similar-looking landforms, a more practical definition for 'alluvial fans' is a fan-like depositional feature that is located where a channel loses (or did lose, at one time) confinement. It must also be, recognized that some fans are active today while others are relict features that evolved during the deglacial period following the most recent Fraser glaciation. Many older fans in the Okanagan and across British Columbia were formed as paraglacial features (Ryder 1971a,b), evolving near glaciers but not directly influenced by the ice, but are not presently active (i.e., growing or evolving). There is the potential for reactivation under certain climatological conditions and when land management practices lead to slope destabilization. Road construction and runoff diversions can activate portions of relict fans that would otherwise remain stable. Thus, there is an important need to understand both active and inactive alluvial fans from the perspective of hazard avoidance and mitigation.

There is growing interest in alluvial fans in the Okanagan Basin because:

(1) they are characterized by complex hydrologic processes such as surface-groundwater exchanges that influence aquatic ecosystem health;

(2) they are areas where surface-groundwater connectivity is intimate, making it difficult to close out water budgets, thereby hampering the ability to determine realistic targets for allowable water extraction and licensing for water supply purposes such as irrigation and domestic withdrawals while also sustaining environmental flow needs;

(3) they are preferred sites for construction/development, agriculture, and aggregate extraction because of the gentle slopes and generally well-drained, unconsolidated materials;

(4) they are areas with the richest forest potential because of water availability and loose soils, and therefore a focus of timber harvesting;

(5) they are areas prone to geotechnical instabilities (e.g., debris flows, mud slides) and periodic flooding, thereby posing hazards to humans and critical infrastructure; and

(6) their periodic disturbance by sediment transport events creates successional vegetation communities (e.g., trembling aspen, cottonwood stands) that are of ecological importance (de Scally 1999).

The overall purpose of this Primer is to provide an easily-read source of information on alluvial fan hydrology for environmental managers, decision makers, and elected officials. The document is divided into sections that: (1) place alluvial fans in the context of mass movements; (2) describe the primary features of alluvial fans, including their evolution and internal stratigraphy; (3) summarize the types of

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[1] Harvey (2005; 2018) provides a concise summary of fan geometry in the context of tectonic upheavals and climate change, especially the potential for alternating phases of fan aggradation and dissection (with fanhead trenching) that substantially modify the complex internal architecture of fans.

fan-like features found in the Okanagan Basin; (4) discuss the importance of fans; (5) point to some of the management challenges associated with fan occupation and use; and (6) identify critical knowledge gaps that (7) lead to recommendations that will enable an improved understanding of alluvial fans in the Okanagan region.

ALLUVIAL FANS and MASS MOVEMENTS

There are many different types of fan-like features found in the Okanagan Basin, but they all have their origin in 'mass movements' (Carson and Kirkby 1972), which refers to processes on hillslopes and mountain sides that cause surface materials to move downslope. The type of deposit is characteristically diagnostic of the movement type (Figure 2). Some mass movement processes act rapidly (e.g., rock falls, debris avalanches) whereas others are characterized by slow downslope movement (e.g., soil creep). Moisture conditions are critical in controlling the style of mass movement, and these two features (speed and moisture) are the central features of the classification system shown in Figure 2. The type of material (boulders, cobbles, gravel, sand, clay) can also control the types of landforms that are created due to the mass movement (refer to the small diagrams surrounding the central triangle in Figure 2). There are landform features created by the pervasive and relentless action of gravity alone (e.g., rock slides) while others involve materials that are partly or completely saturated with water (e.g., debris flows) or are moved directly by flowing water (i.e., alluvial deposits).

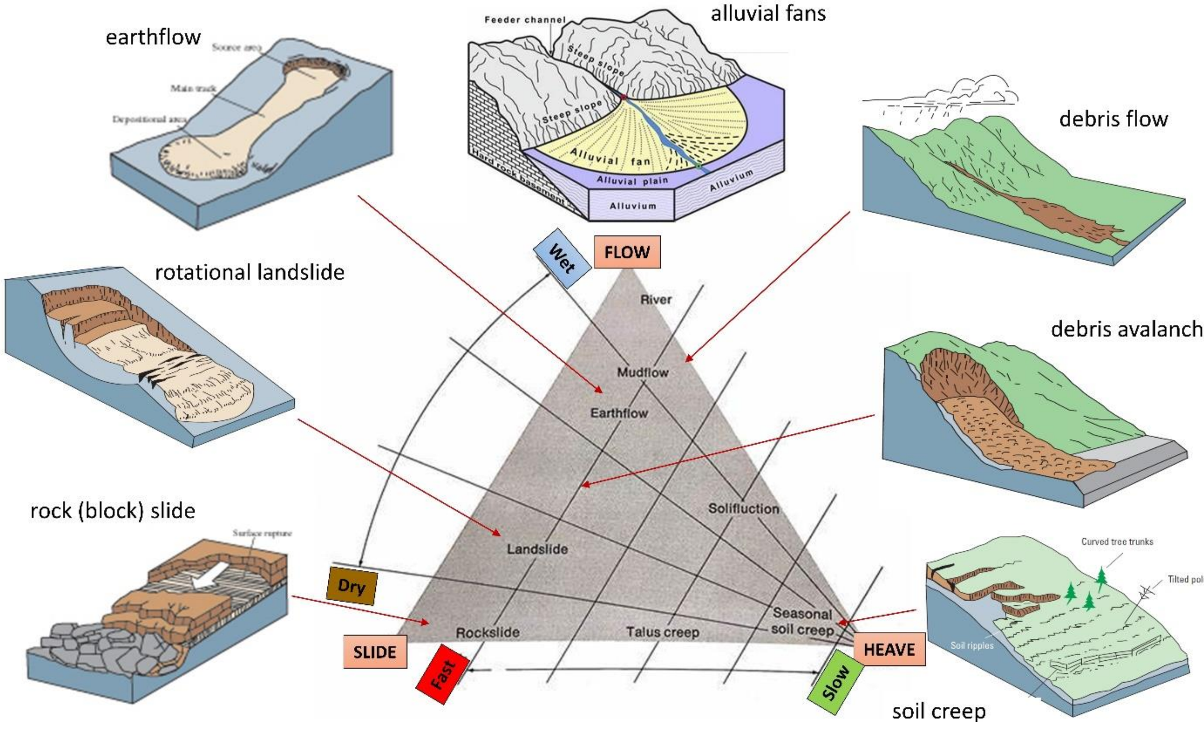

Figure 2: Types of mass movements on hillslopes, ranging from colluvial-dominated features (e.g., rock slides, soil creep) to alluvial landforms (e.g., alluvial fans) that are formed by flowing water. Central triangle schematic is after Carson and Kirkby (1972). Alluvial fan image is from Richards (1982). Graphic images of mass movement types are from https://pubs.usgs.gov/fs/2004/3072/images/Fig3grouping-2LG.jpg.

The quintessential alluvial fan (top diagram of Figure 2) is not actually a specific type of mass movement, but rather a depositional landform created when a stream drops its sediment load, typically in locations where the channel emanating from a canyon or deep tributary valley transitions to an unconfined valley with gentler gradient (Figure 1). Thus, the classic alluvial fan is truly an 'alluvial' feature (formed by running water in a stream or river) rather than a hillslope feature formed by mass movements such as debris flows. Nevertheless, there are a range of landforms that are very similar to alluvial fans in terms of their overall shape or lobate topology.

Figure 2 shows that many debris flow and earth flow deposits look very similar to alluvial fans. These landforms originate in mass movements that were initiated by geotechnical instabilities on the hillslope, often due to intense rainstorms leading to soil saturation, creating a landslide scar upslope of the deposit. The classic alluvial fan exists within a continuum of similar-looking features ranging from individual lobe deposits due to debris flows (and earthflows) at one end, through 'true' low-angle alluvial fans, to sub-aqueous deltas at the other end (Harvey 2018). **For the purposes of this document, all such fan-like features will be referred to as 'alluvial fans' with the understanding that very steeply inclined depositional cones created by rock falls and rock (debris) slides are excluded**. These colluvial[2] cones and talus slopes are high-mountain features that don't require flowing water and are quite different in internal structure and particle size characteristics.

FEATURES, EVOLUTION, and STRATIGRAPHY

Classic alluvial fans and fan-like deposits can be identified by several diagnostic features or elements (Figure 3), which include: (i) the *drainage basin* (or contributing area) that provides the source of water and sediment to the fan; (ii) the *feeder channel*; (iii) the *fan apex (or head****)***; (iv) the *active depositional lobe*; (v) a *distributary channel network*; and (vi) a complex system of *debris levees*. The ***drainage basin*** serves as the source area for the sediment and water that eventually finds its way to the alluvial fan via a network of drainage channels. The stream network within the drainage basin often looks like the dendritic branches of a tree with a ***feeder channel*** or main trunk stream and many tributaries of varying size that feed into the main stream at branch bifurcations. The tributary channels become progressively smaller farther away from the main stream as they dissect the steeper landscape at higher elevations close to the drainage divide.

In the headwater regions, hillslope processes deliver sediment to the smallest, highest-elevation, first-order streams, which then deliver water and sediment to progressively larger streams of higher order farther down the drainage basin at lower elevations. The main feeder channel serves to collect all the transported material from above and moves it through the fan apex and eventually onto the fan surface. The ***fan apex*** marks the location where there is a transition from erosional conditions upslope to a depositional environment downslope, stimulated by the change in gradient from steep to gently sloping terrain (e.g., from a hillside to a valley bottom). As water (and sediment) moves past the narrow throat section of the fan apex, it flows out onto the flatter landscape below, leading to slowing of the spreading flow that is accompanied with sediment deposition. As more and more sediment is deposited near the

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[2] Alluvial material is a general term used to describe loose materials that have been moved by flowing water in a relatively continuous process, such as sand and gravel transport by a stream. Transport by water implies that there is an upper size limit for the particles that were moved from one location to another. In contrast, colluvial materials are loose, unconsolidated materials that have been deposited at the base of a slope, typically under the influence of gravity through such processes as soil creep, rock fall, and debris slides, although water is often involved. There is no limit on the size of particles moved via colluvial processes (e.g., massive boulders).

apex, the alluvial fan builds vertically and extends outward laterally and longitudinally. This process of sediment delivery and progressive deposition downstream of the apex, is what builds the fan-like deposit that is characteristic of all alluvial fans. Sediment deposition on fans can be continuous, but the largest volume of sediment deposition usually occurs during flood events (or debris flow events).

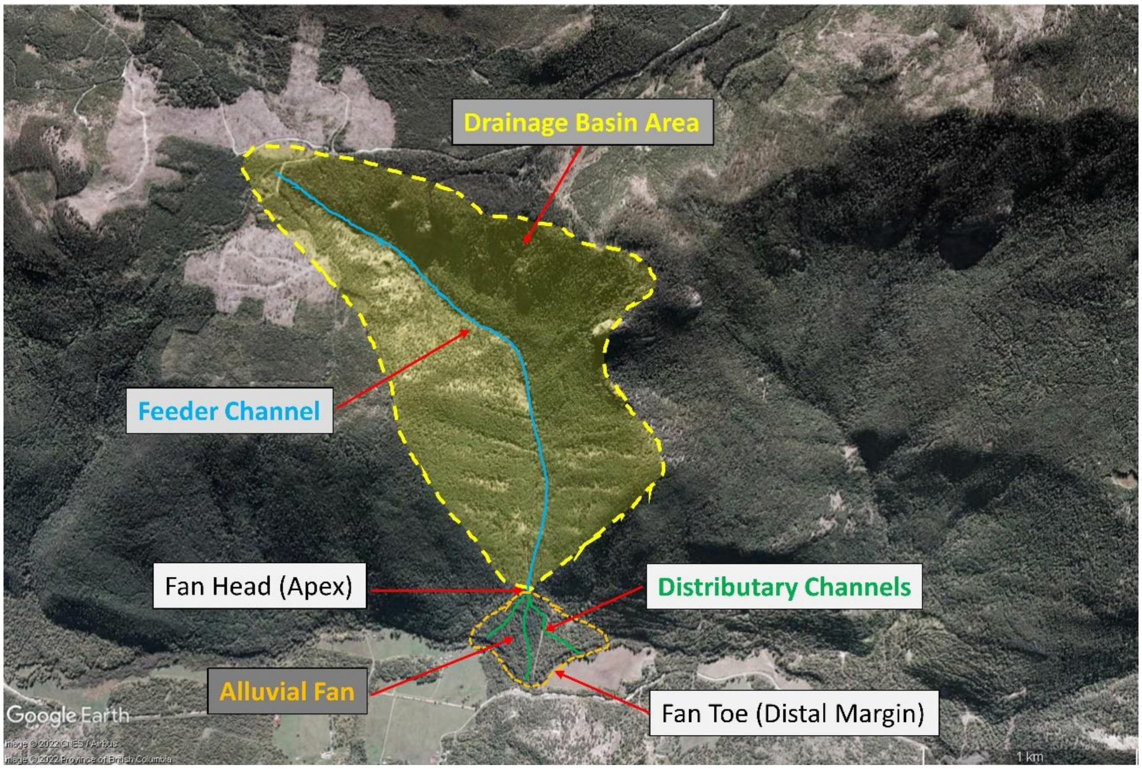

Figure 3: Primary components of an alluvial fan complex, including source area (drainage basin) above the fan apex and the actual depositional feature below the apex known as the alluvial fan. This example is about 10 km along Creighton Valley Road, just east of Lumby, BC. View looking south.

Alluvial fans evolve with time as more and more sediment is moved through the fan apex and deposited on the fan surface. The distal margin or fan toe marks the limit to which sediment has been delivered to the fan from the drainage basin, and it usually has an arcuate form. However, erosion at the toe by streams and rivers (or wave process in lakes) can cause truncation of this arcuate form thereby changing the geometry and limiting the growth of alluvial fans (Leeder and Mack 2001).

On the fan surface, there is typically a network of 'distributary' channels that serve to carry water and sediment away from the fan apex. The ***distributary network*** often looks like a mirror image of the upstream drainage network. In the upstream drainage basin, the small tributary channels feed into the main trunk stream; on the fan, the distributary network serves to distribute or transport the flow away from the main active channel. Thus, the water and sediments moving through the fan apex are 'distributed' outward across the fan surface. Many of the distributaries terminate on the fan surface due to loss of water by infiltration or to spreading of water due to lack of channel confinement. The main active channel usually has ***debris levees*** on either side (Figure 4) which serve to confine the flow to some degree. However, the debris levees typically consist of large, unconsolidated materials and therefore are porous. They form during extreme events (e.g., floods, debris flows) when the channel itself does not have sufficient capacity to convey the slurry that it receives from upstream, so the material in transport is deposited on top of the banks and only a short distance away from the channel.

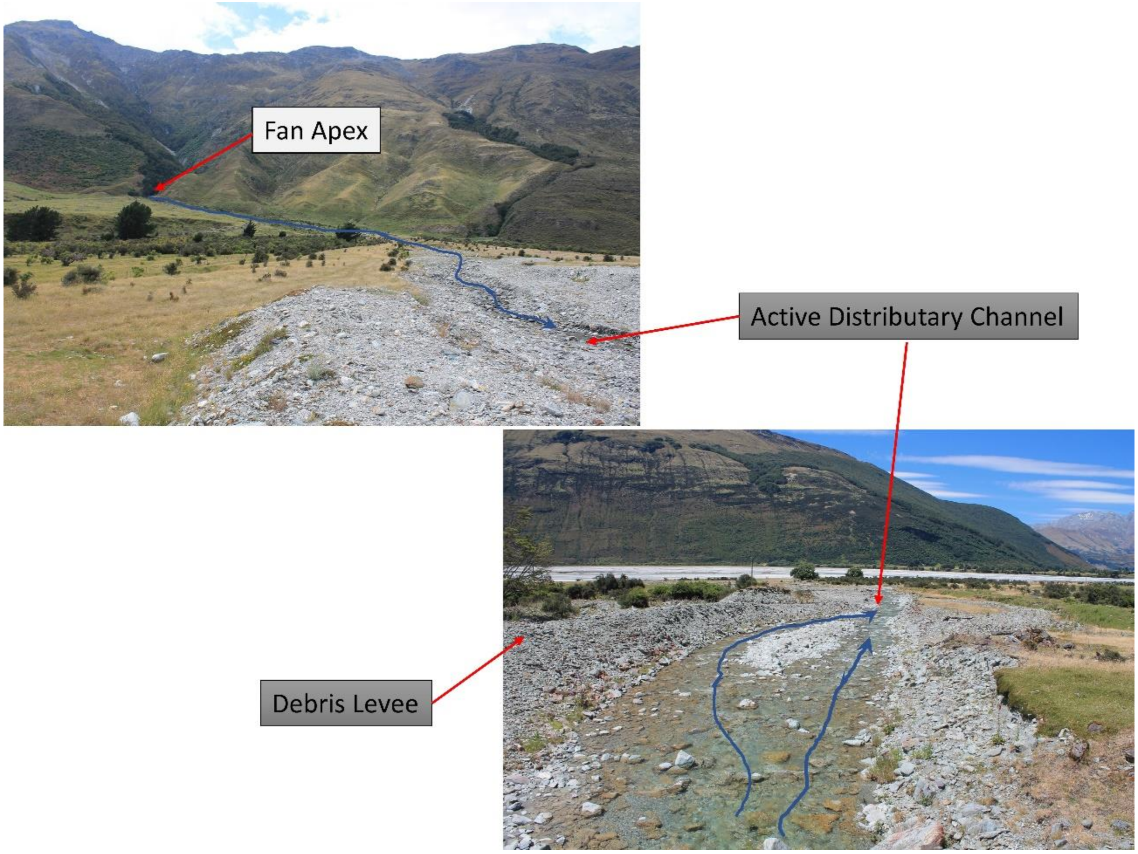

Figure 4: Components of alluvial fans highlighting the main active channel of the distributary network with debris levees (photographs: Bernard Bauer CC BY-NC)

The debris levees, and indeed the entire distributary network, are very unstable and prone to rapid change. Typically, sections of the main channel are only active and dominant for a short time (years to decades). Material that moves through the channel to the distal margin of the fan causes the toe region to accumulate sediment, thereby flattening the overall steepness of the channel from apex to toe. As the channel becomes less steep, it has reduced capacity to sustain flow and transport sediment, so the water slows down leading to more deposition. Eventually, the channel becomes clogged with sediment and is no longer able to convey the incoming water and sediment from above. A critical threshold state is reached whereby the channel is unable to accommodate the next major flooding event, and during that flood, the levees are overtopped and new channels will be carved. The water that cuts through the levees tries to find the shortest, steepest route across the fan surface leading to the toe (i.e., valley bottom), and thereby cuts a new main channel leaving the old active channel abandoned, or left as a smaller distributary channel. This process (known as channel avulsion) is a recurring event in the evolution of alluvial fans, and fans will have a history of the active main channel shifting its position across the entire fan surface at different times. It is the primary mechanism by which the fan builds its classic conical shape, with the steepest slopes near the apex and more gradual slopes toward the distal end (toe) of the deposit.

A history of recurring avulsions amidst progressive, long-term sediment delivery to the fan surface leads to the internal stratigraphy (layering and geometry of sediments) of alluvial fans being highly complex. The longitudinal meandering of avulsed channels leads to erosion of channel margins along the surface of the fan, and after an avulsion the active channel will be abandoned. The remnant channel becomes a zone of weathering and gradual sediment accumulation. In cross-section, there will be multiple lenses of varying, poorly-sorted materials ranging in size from mud/silt/sand to gravel and boulders. Figure 5 shows an idealized alluvial fan in planform created by a combination of streamflow (ongoing) and debris flow (periodic or catastrophic) deposits. Cross-section (A-B) shows the lens-like configuration of the channels and lobes whereas the longitudinal section (C-D) shows the discontinuous nature of the channels that are truncated due to ongoing meandering of the main channel and periodic avulsions of distributary channels. The longitudinal section (C-D) also provides a sense of how the deposit has aggraded vertically and extended laterally. As a consequence, the fan gradient is steepest close to the apex and typically becomes progressively less steep towards the distal fanbase (close to the toe) yielding a classically concave-upward longitudinal profile.

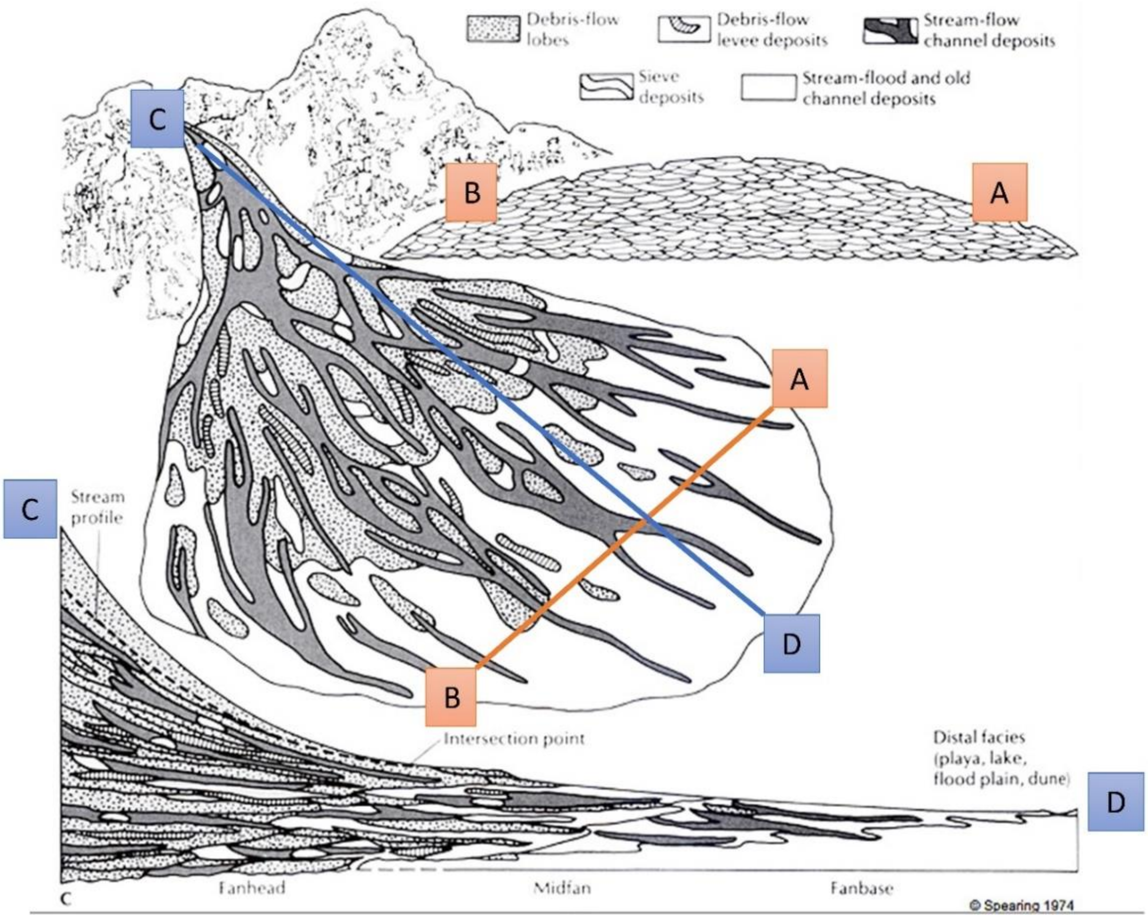

Figure 5: Schematic of an idealized alluvial fan showing planform with internal stratigraphy across a cross-section (A-B) and longitudinal section (C-D). From Spearing (1974).

The idealized alluvial fan shown in Figure 5 is an example of what Bull (1977) referred to as a ‘streamflow’ type fan (Figure 6a) because the dominant formative processes are related to flowing water in channels. They tend to have gentle slopes (usually less than 5 degrees on average, although steeper toward the apex), and the surfaces can be barren or completely vegetated. The mid to lower sections often contain braided channels that shift in position and change their configuration frequently. Channel widths are large relative to flow depth, and during the summer the channels are often dry. In contrast, Bull (1977) also identified ‘debris flow’ type fans (Figure 6b), which have steeper slopes (up to 15 degrees) and tend to be smaller in size and not obviously fan shaped in many instances. Episodic debris flows are the dominant formative process, and these create boulder-lined levees with trapezoidal channels and adjacent boulder lobes. Although the channels are actively altered, they tend to be deeply incised near the apex and do not migrate laterally until an avulsion occurs. At the distal margins, there are lobate deposits that mark the farthest extent of individual debris flow events. The dominance of debris flow activity leads to a longitudinal profile that is approximately linear rather than concave upward as with streamflow fans.

The sedimentary architecture of streamflow fans and debris flow fans is usually quite different. Streamflow fans tend to be characterised by partly- to well-sorted[3] sediments that show stratification (layering), usually with internal structures that have clast-supported large particles (i.e., cobble-sized material in direct contact with each other while the spaces between the large particles are infilled with fine-grained sediment). In contrast, debris flow fans are characterised by unsorted and unstratified sediment, which closely resembles glacial till but is typically less compact. The large clasts are matrix-supported (i.e. cobble- and boulder-sized material are embedded within and supported by the surrounding finer material). In both types of fans, there is usually a discernable particle-size fining sequence in the downstream direction. On streamflow fans, this can be attributed to the fact that the water flow that is confined above the fan apex has considerable power to transport sediment, but once the flow passes the apex, the stream loses energy. The channel slope decreases, the width increases, and there is usually water infiltration into the channel bed. Thus, the sediment transporting capacity decreases down the axis of the fan, and only the finer sediments (silts and clays) remain mobile at the fan toe. On debris flow fans, even small ones, there can be a downslope fining sequence, which is less obvious. This is because a debris flow moving through the apex and spilling out on to the fan surface will also lose energy. The coarsest materials travel only a short distance, and as the slurry continues to move downslope there is deposition on the levee margins. The remaining water and fine sediments continue to travel down the fan surface as hyperconcentrated[4] flows, until all the energy is lost and most of the fine material in transport is deposited as a lobe.

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[3] Sorting describes how similar in size the sediments are in a given deposit. A well-sorted material means that the processes moving the sediment had similar energy over time. For example, a consistently flowing stream will create a well-sorted sediment layer at its base. Poor sorting of sediment means the mechanism transport has varied considerably over time, such as widely varying flows in a flood event, or the sediment results from something like a debris flow or rock fall, where all grain sizes are picked up and moved together regardless of size.

[4] Fluvial flow is when flowing water carries sediment as a minor component by volume. A debris flow is a heavy slurry of rock, sediment and water that flows like a fluid, but is mainly solids. Hyperconcentrated flow falls in the middle, with sediment making up 5 to 60% of the flowing fluid, and water makes up the rest.

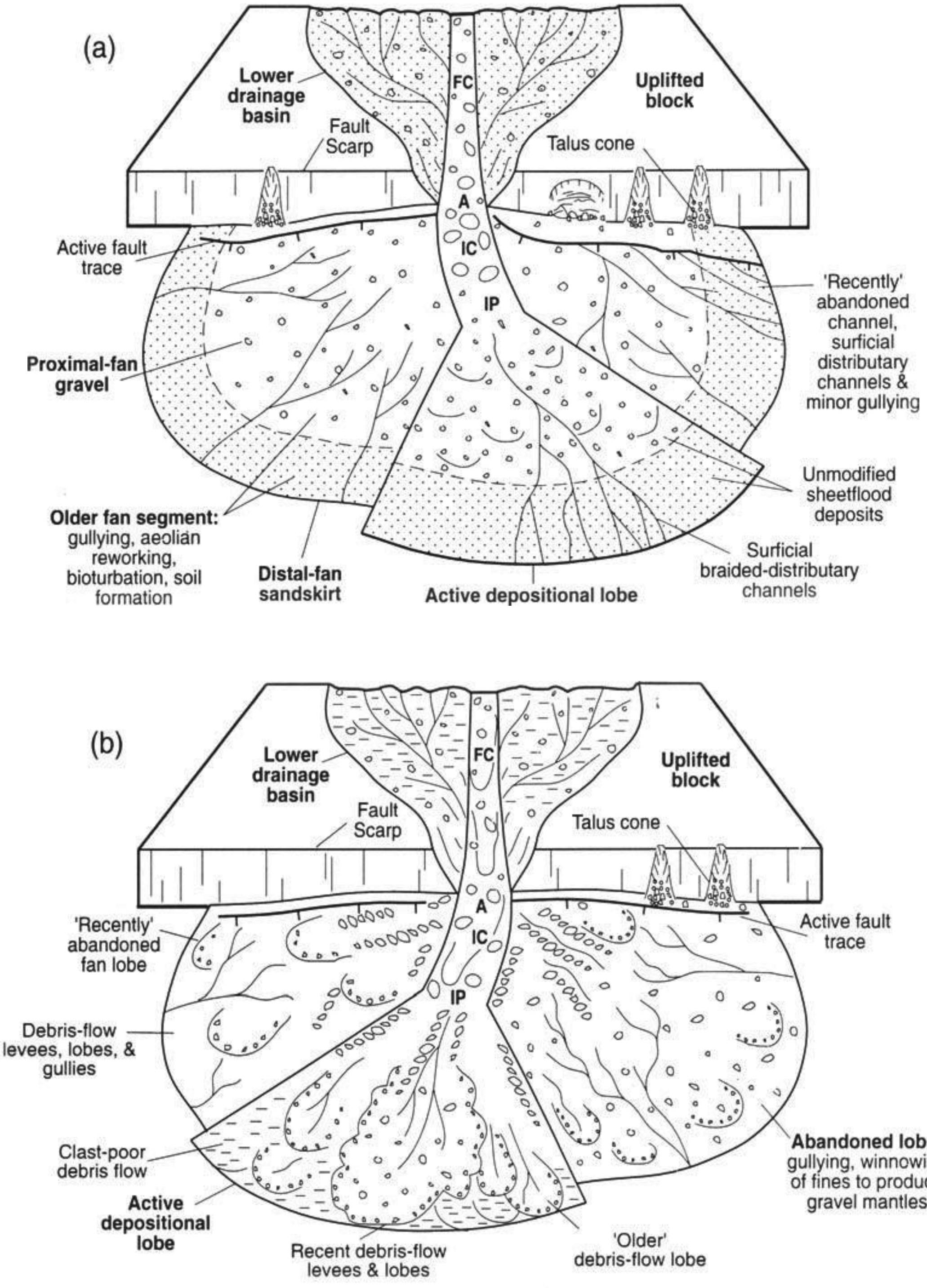

Figure 6: Schematic diagram of the primary features of (a) a streamflow-dominated fan and (b) a debris-flow-dominated fan. A = fan apex; FC = feeder channel; IC = incised channel, and IP = fan intersection point. (from Blair and McPherson 1994)

In reality, differentiation between streamflow fans and debris flow fans is rarely easily accomplished in the field because alluvial fans are often affected by both streamflow and debris flows at different times in their evolution, and often their surfaces are reworked by development and land-use activity. Even the classic debris flow fan can be altered by seasonal or episodic streamflow events during wet periods. Some debris flow fans in humid climatic settings have perennial streams (with flow all year around). Hence, evidence that may be diagnostic of debris-flow activity on fans is often modified or removed by fluvial activity.

Some fans formed under very different conditions than the current day, and may retain some geomorphic signatures from their original formation. Very old and relict fans that evolved over long periods of geologic time may have been influenced by a range of processes that incorporate non-alluvial deposits within the fan stratigraphic sequence (Neton et al. 1994; Petalas 2013). Examples of such deposits might include: superimposed marine or lakebed deposits over alluvial fan sequences as local water levels change; burial of ancient soils (paleosols); aeolian (wind-blown) deposits of loess (fine soil) or dune sand during arid phases or after uplift, and glacial deposits such as kame and drift[5]. Thus, the sedimentary architecture can be complex with alternating sequences of deposits of varying origin (i.e., alluvial and colluvial), which is often the case for Okanagan Basin fans. The forest sector in British Columbia uses three categories of fans based on the dominant contemporary processes – flood fans, debris flood fans, and debris flow fans.

Some recent alluvial fans are very small, especially when the contributing area is small, but older fans that have been active for centuries and longer can be quite extensive in area. There is a close association between alluvial fan size and the drainage area upstream of the fan apex that supplies it with water and sediment (Figure 7). Bull (1962) proposed the following equation to characterize this relationship:

$$A_f = x(A_d)^y$$

where A_f is surface area of alluvial fan, A_d is area of drainage basin feeding the fan, x is an empirical coefficient (typically between 0.1 to 2.2) depending on precipitation regime, soil infiltration capacity, and a range of lithologic and geologic factors, and y is an empirical coefficient (ranging between 0.7 to 1.1) depending mostly on sediment supply and potential for sediment delivery to the fan.

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[5] Kame are sediments that accumulate along the sides of glaciers or on the top of a glacier while the glacier is present. They remain behind when the glacier melts. Kame may build up on the side of the glacier, and when the glacier retreats, can leave behind terraces. The terraces along the Naramata bench are an example. Drift is a general term for many different types of glacial sediments that are deposited by the glacier ice, or washed out the front of the glacier by meltwater.

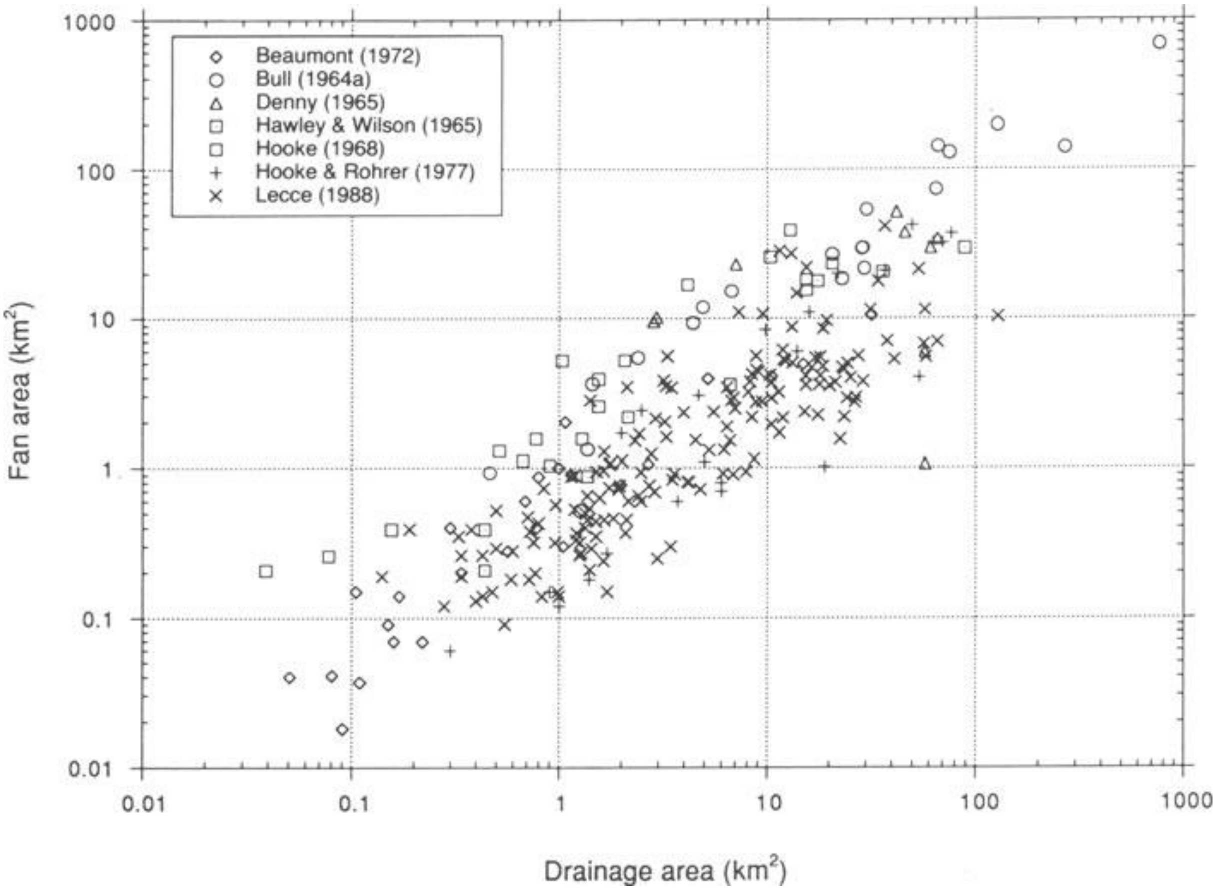

Figure 7: Relationship between fan area and the contributing drainage area that feeds water and sediment to the fan (from Blair and McPherson 1994).

The statistical relationship proposed by Bull (1962) explains, in part, why the fan-like features found along the valley bottoms of the Okanagan Basin are typically much larger than those features found at mid to high elevations (because the drainage areas supplying the valley bottom fans are larger). However, there would be considerably more scatter in a similar graph of alluvial fan size in British Columbia. There are several reasons for this. In the mountainous terrain of BC, the growth of fans is usually constrained by topography (i.e., valley side walls). In addition, the humid climate implies that rivers and streams are much more prevalent than in arid environments (where most fan research has taken place historically), and often the alluvial fans emanating into river valleys are truncated at the toe and re-shaped at the distal margins. Perhaps more importantly, the size of a fan is dependent to a large extent on sediment production and delivery to the fan surface, which, given our bioclimatic conditions and recent glacial history, are generally very active (although locally complex) in contrast to the desert South-West of the United States.

As mentioned earlier, this Primer is not concerned with hillslope processes and forms that occur in steep mountainous terrain. Figure 8 shows an example of a debris cone that is not included in the mix of alluvial fan features described herein. It is presented only to provide the reader with a perspective on what is not an alluvial fan for the purposes of this Primer.

Figure 8: A debris (talus) cone that has a fan-like topology but is considerably steeper than an alluvial fan and differs in terms of processes, sedimentology, and stratigraphy. It is not considered an alluvial fan. (Photo credit: South Island, New Zealand, taken by Bernard Bauer CC BY-NC).

TYPES of FANS in the OKANAGAN BASIN

Alluvial fans in the Okanagan Basin can be categorized loosely in terms of their location with respect to elevation (i.e., low versus mid to high elevation). The low elevation fans tend to have more of a classic fan-shaped appearance as they are less confined when reaching the valley bottom. The mid to high elevation fans may also have classic fan shapes but are generally smaller and/or elongated because of valley confinement. In some instances, their appearance is not fan-like but rather similar to a wide, braided reach of a stream because of the loss of channel confinement locally.

Classic mountain-front fans at low elevations

Perhaps the most prominent and easily recognizable examples of alluvial fans in the Okanagan are those that are found on the major valley bottoms along the margins of mountain fronts. These typically large fans have the attributes of classic streamflow alluvial fans found in arid environments, and they are often referred to as ‘mountain-front fans.’ They form in the same manner as classic alluvial fans, with sediment building vertically upwards and laterally outwards as the distributary channel system shifts from side-to-side during the evolution of the landform. Their size is roughly proportional to the size of the drainage basin that feeds the fan, as per the relationship proposed by Bull (1962), but there can be great variability because of the glacial history of the Okanagan region. Some fans were formed during deglaciation when precipitation, snowmelt, vegetation cover and sediment loads were very different and are being modified only slightly in the contemporary environment. This is particularly true in the South Okanagan where it is hotter and drier with many creeks being ephemeral. Indeed, many alluvial fans in the south, such as the examples at the bottom of Hester Creek and Tinhorn Creek (Figure 9), are relatively stable and therefore have permanent human occupancy (e.g., vineyards, houses, roads). These stable-appearing fans are still subject to infrequent events of major impact, whether natural such as intense rainstorms or of human origin such as the failure of an earthen water-supply dam, which can lead to devastating consequences as witnessed by the Testalinden debris flow disaster in 2010 (Tannant 2015).

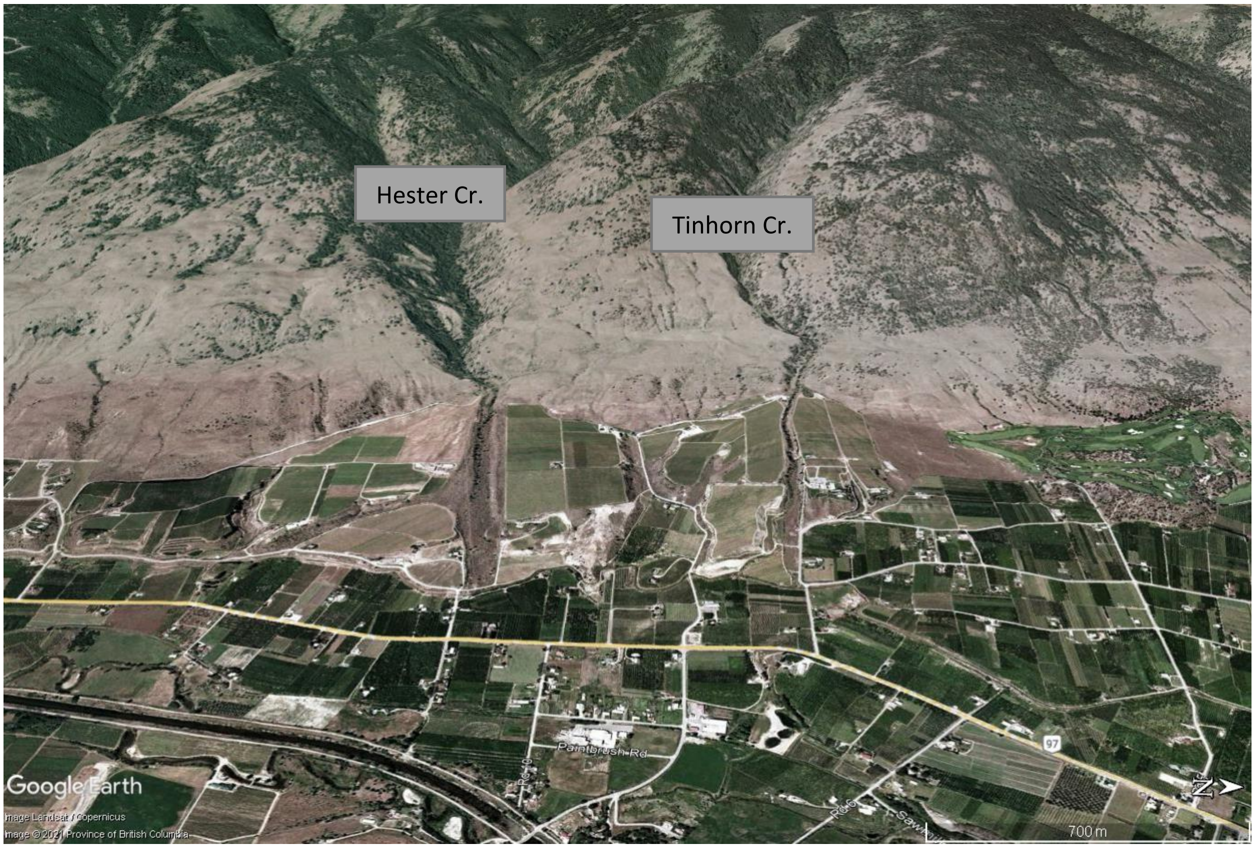

Figure 9: Examples of large, classic-style alluvial fans found along the valley bottom at the margin of mountain fronts. Hester Creek on left and Tinhorn Creek on right. Note that both creeks are ephemeral and the channels terminate at the fan toe. (Image from Google Earth)

In the North Okanagan, where it is cooler and wetter, there are also mountain-front fans, but they are often not as prominent as in the South Okanagan and are often vegetated with trees. The sizes of the fans in the north are also related to drainage basin area, but since many of the feeding basins are small, so too are the fans. Moreover, the creeks that deliver water and sediment to the fan are usually perennial, and as such, the fan surfaces tend to be more active currently than farther south. Many of the ephemeral creeks in the south lose water to the ground and therefore terminate along the fan surface or somewhere close to the fan margin. In contrast, the perennial creeks in the north, although still losing water to the ground in many locations, sustain their flow in channels that extend far past the fan margin. This is the case with the creeks shown in Figure 10 that eventually feed Fortune Creek, which flows to the north to join the Shuswap River.

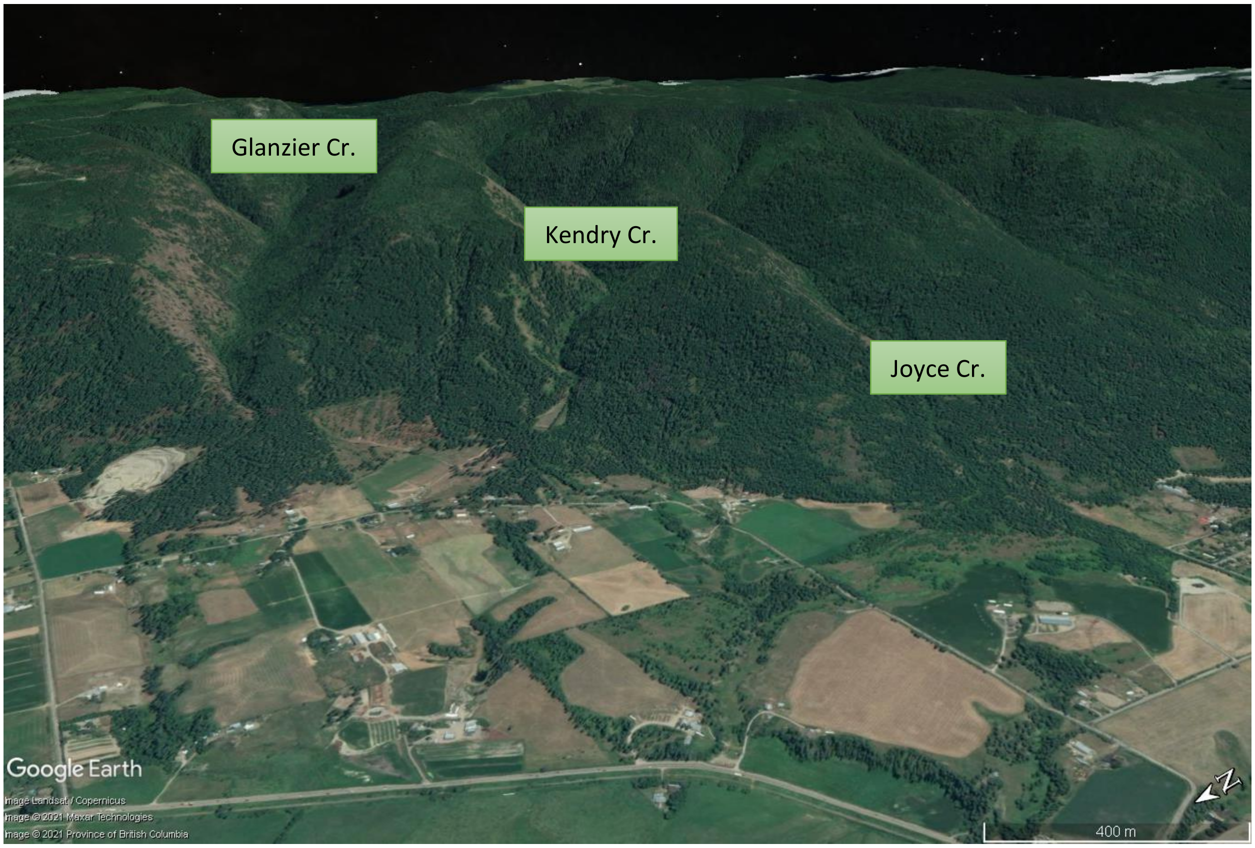

Figure 10: Examples of valley-bottom (mountain-front) fans from the North Okanagan. Glanzier Creek on the left; Kendry Creek in the middle; Joyce Creek on right. All these creeks are perennial, and the flows move past the fan toe and across the valley bottom, beneath Hwy 97 (in lower photo) through culverts into drainage ditches, and eventually join Fortune Creek. Note that the fan below Glanzier Creek (left side of photo) is being mined for aggregate. Image from Google Earth.

Fan Deltas

Fan deltas have distinctive fan-like shapes and they also form where a creek that carries water and sediment from the contributing drainage basin loses energy and causes deposition. However, in this case, the creek spills into a lake rather than onto a valley floor, and the modes of sediment deposition are somewhat different than for a subaerial alluvial fan (or classic fluvial deltas such as found on the Mississippi River or Nile River). Fan deltas are interesting features because they began to form as fluvial deltas (entirely submerged beneath water) during high lake stages following the Fraser glaciation. Subsequent lowering of lake levels in post-glacial times exposed the fan delta deposits to subaerial processes, and at least part of their recent evolution is similar to what happens on alluvial fans. The most prominent fan deltas are found on the western side of Okanagan Lake, Fintry being a prime example (Figures 11 and 12).

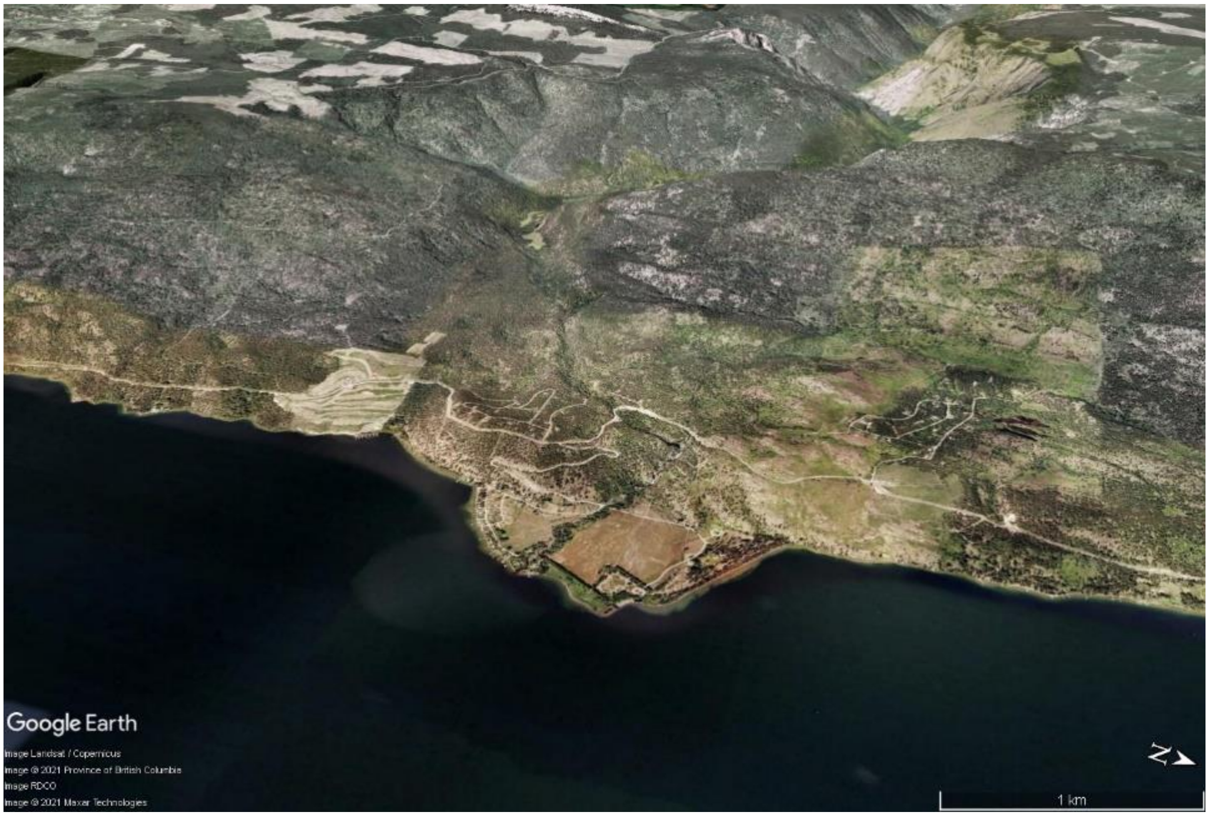

Figure 11: Aerial image of the Fintry fan delta in the North Okanagan, looking west-southwest. Image from Google Earth.

Approximately 10,000 years ago, Glacial Lake Penticton (GLP) extended from roughly McIntyre Bluff in the south to north of Enderby, and had lake levels as high as approximately 520 m above sea level (1700 ft asl) during the Long Lake Stage (Fulton 1969). This is much higher than the current lake level range of 341-343 m asl. The position of the GLP shoreline at that time coincides roughly with a topographical contour line today that separates the steep mountain front from the flatter Fintry fan surface, which now lies above the contemporary shoreline of Okanagan Lake (Figure 12). Shorts Creek delivers sediment to the fan apex and causes erosion in the channel farther downstream along the length of the fan. However, there are very few modern overbank events that modify the Fintry fan surface, and it has been used for agricultural purposes since the 1800s. The distal margin of the fan delta is continually reworked by the action of waves and lake currents thereby smoothing out any irregularities at the toe that may have existed due to avulsions of the distributary channels and lobe extension. The marginal slope offshore of the toe is very steep, diving to the lake bottom very quickly, which means that fan progradation is unlikely in the contemporary environment (i.e., minimal sediment delivery via Shorts Creek).

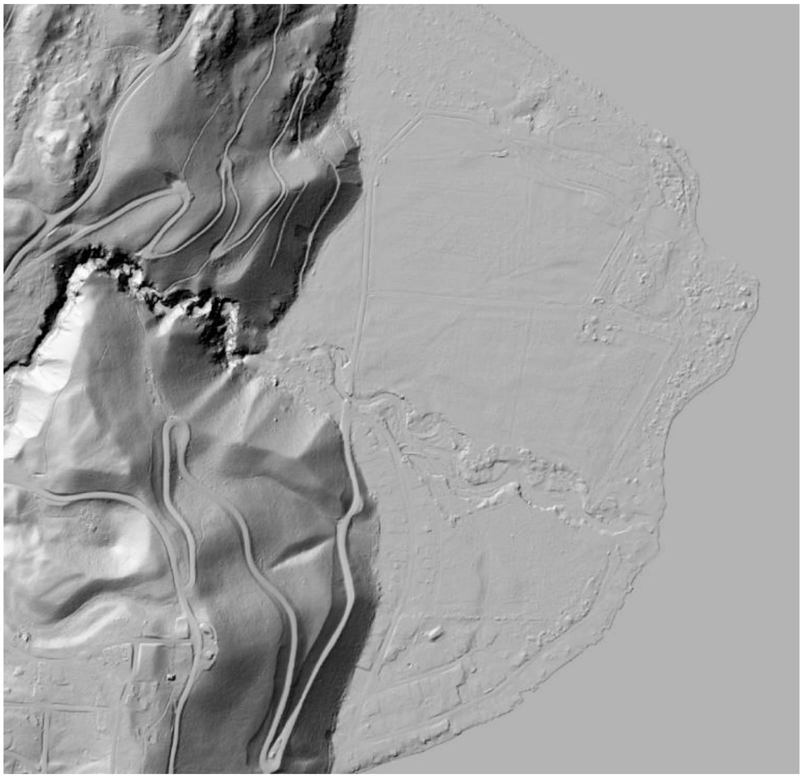

Figure 12: LiDAR-based digital elevation model of the Fintry fan delta showing overall geometry of the fan and position of Shorts Creek as it flows through the fan apex toward the distal margin of the fan complex. Okanagan Lake, at right, is rendered as a featureless plain in this image. (LiDAR digital elevation model downloaded from BC Government LiDAR Portal)

Although fan deltas in the Okanagan Basin had their origins as sub-aqueous deltas during glacial times, they have a somewhat different geometry and structure than active deltas that exist in the Okanagan today. Figure 13 shows two examples of deltas forming at the north end of Osoyoos Lake. The delta forming at the mouth of the Okanagan River (upper left of photo) is basically an extension of the marshy lower floodplain of the river. It is comprised of fine-grained sediment (clays, silts, fine sands) and is prograding southward into the shallow northern basin of Osoyoos Lake. It is a classic river-dominated (fluvial) type of delta, also referred to as a "bird's foot" delta because of the depositional protrusions that extend into the lake. The best example of this type of delta is the Mississippi River delta. Similar in nature, but not quite as well developed is the delta shown in Figure 13 at the mouth of Nk'Mip (Inkaneep) Creek (top middle of photo). The delta forming at the mouth of Mission Creek (not shown) is another example. These fluvial deltas differ from fan deltas in two primary ways: (1) fan deltas are usually comprised of coarse-grained materials (e.g., cobble, gravel, coarse sand) with interbedded layers of muds; and (2) the fan delta surface is exposed to subaerial processes with only the distal margins prone to reworking by waves and lake currents. In contrast, subaqueous processes are the dominant mechanisms of delta progradation and evolution. It is worth bearing in mind, however, that due to their history of formation, delta fans often have complex internal stratigraphy with elements of size gradation from apex to margins as well as lenses of alternating materials due to channel shifting and braiding.

Figure 13: Two examples of deltas forming at the north end of Osoyoos Lake. Upper left is from the channelized Okanagan River and the centre one is from Nk'Mip (Inkaneep) Creek. Image from Google Earth.

Mid to High Elevation Fans

Most mid to high elevation fans are relatively small and are affected by a mix of processes that dictate their geometry and morphometry. In all cases, however, sediment deposition on the fan is strongly controlled by local changes in river slope that force the transition from erosion in the steeper upslope contributing areas to deposition farther downslope. These local transitions in relative elevation and channel slope often take the form of tributary junctions, topographic breaks-in-slope from steep to shallow gradient, or streams flowing into mountain lakes and ponds. Because the contributing drainage basins can be small and steep, there are often debris flows, earthflows, rock falls, and other colluvial processes that deliver sediment to the feeder channels, and thence to the apex and onto the fan surface during major events. High elevation fans may also have substantial snowpack accumulation during the winter, leading to snow avalanches that can deliver sediment to the fan. Significant spring freshet flows in the creeks can scour the channels of debris and modify the fan surface. The nature of the surface sediments on these small fans can provide a reliable indicator of dominant processes that are currently active (Gómez-Villar and García-Ruiz 2000; de Scally and Owens 2005).

Within large drainage basins, there can be a series of smaller, nested drainage basins at different elevations associated with tributaries, each with the potential to evolve a fan. Figure 14 shows an example of a mid elevation fan that formed where Dulton Creek (the tributary) joins with Vaseux Creek. The Dulton Creek fan is an inactive feature that may have formed at a high lake stage during the last deglaciation. Note that Vaseux Creek has a very large, low-elevation fan at its valley base (just north of Gallagher Lake) with several diversion channels and seasonally active distributary channels that splay out from the fan apex. On the right is a braided reach along the active channel.

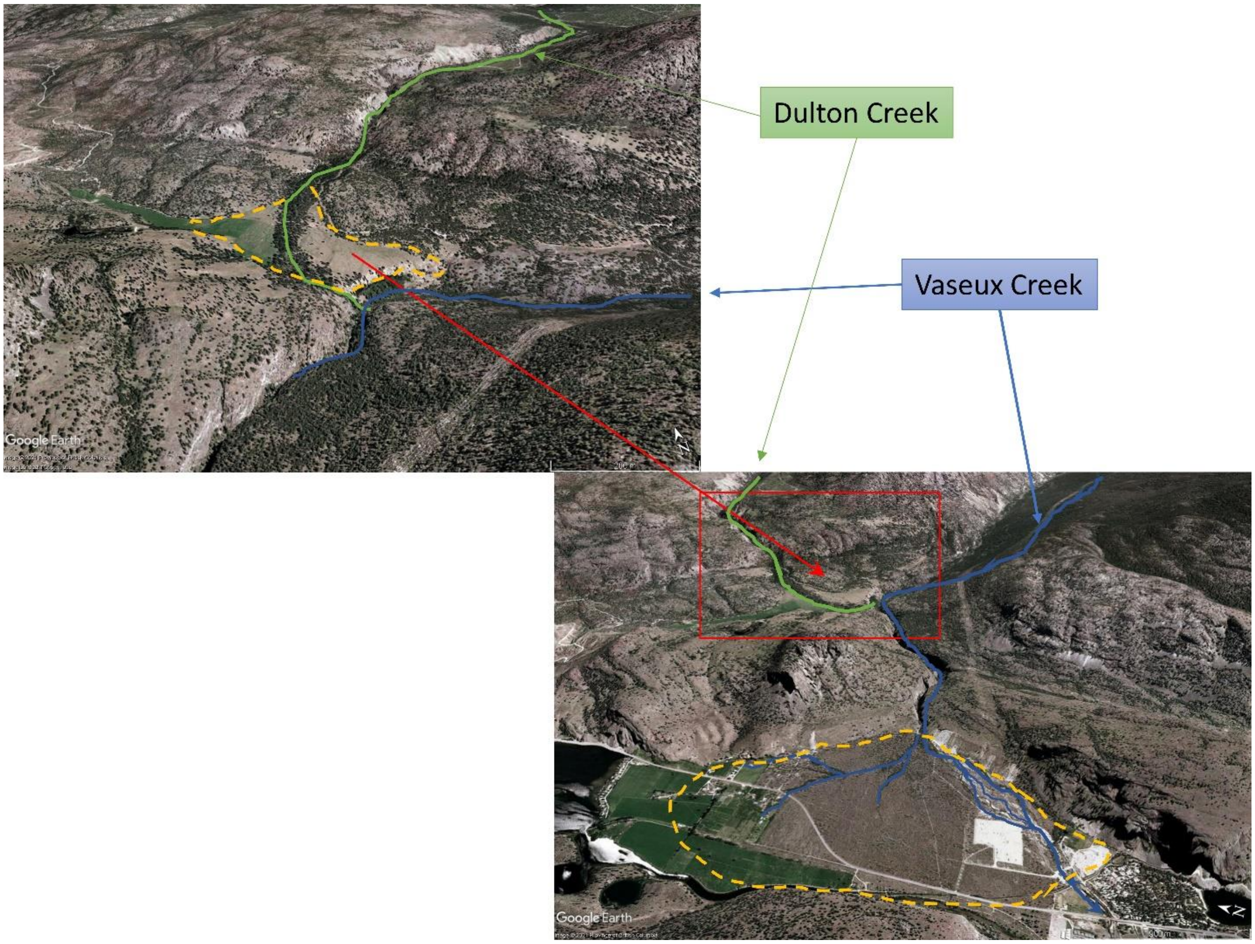

Figure 14: Example of a mid elevation fan at the bottom of Dulton Creek at the junction with Vaseux Creek. Also shown is the low elevation streamflow type fan where Vaseaux Creek encounters the valley bottom (north of Gallagher Lake, to bottom right of photo). Images from Google Earth.

Mid and high elevation fans can also have their origin in streams and rivers that flowed into a lake that no longer exists. Small lakes on the sides of glaciers at high elevations on the valley sides were present during the end of the last glacial period (Paradis et al, 2010). Such glacial-margin lakes may have developed as the largest valley center glaciers melted and retreated providing a source of water that was trapped at upper elevations. Fan deltas developed into these lakes and are now relict features on the landscape. An example is found at 1200 metres elevation on Daves Creek on the hillside east-northeast of Black Mountain (Paradis et al, 2010).

The imagery in Figure 15 and Figure 16 show examples of mid elevation fans that formed at locations where tributary streams join with a main trunk stream because the channel gradients are transitional from steep to shallow. There is a large tributary fan at the junction of Pearson Creek with Mission Creek (middle right of image) that has multiple incised terraces, some of which indicate a relict origin of the higher fan surfaces. Two smaller fans sit on the north side of Mission Creek emanating from unnamed tributary valleys of limited size. Both have had their toe sections eroded by the meandering of Mission Creek, with the fan surfaces sitting far above the present river valley. Interestingly, there are no fans at the base of similar sized tributaries on the south side of the valley, presumably because the meandering tendencies of Mission Creek eroded them in the past. Because these channels are not currently active, they have little capacity to deliver sediment to the valley floor and evolve new fans.

LiDAR imagery (Figure 15a) is particularly useful in identifying mid to high elevation fans in the Okanagan Basin because extensive forest cover usually obscures these features in air photos (Figure 15b). Without the aid of a LiDAR-based, bare-Earth Digital Elevation Model (DEM), the identification of alluvial fans in forested environments is typically accomplished by skilled personnel during field reconnaissance, which can be expensive and time consuming. As such, not all mid to high elevation fans have been identified, with more extensive knowledge developed in forest cut blocks where site-level reviews of forest roads and hazard evaluations are undertaken.

Even in places where mid to high elevation fans are known to exist because of field reconnaissance, not all features can be easily identified using air photos or LiDAR. In the case of the fans shown in Figure 16, which are not immediately apparent to the eye, the first rule of thumb to identify fans is that they occur anywhere that a stream channel, active or relict, loses confinement. The features that are circled in Figure 16a are located on the south side of Vernon Creek near Winfield, and they are virtually invisible on the aerial photo shown in Figure 16b. Yet, they are all known to be active in that avulsions have occurred and will continue to occur.

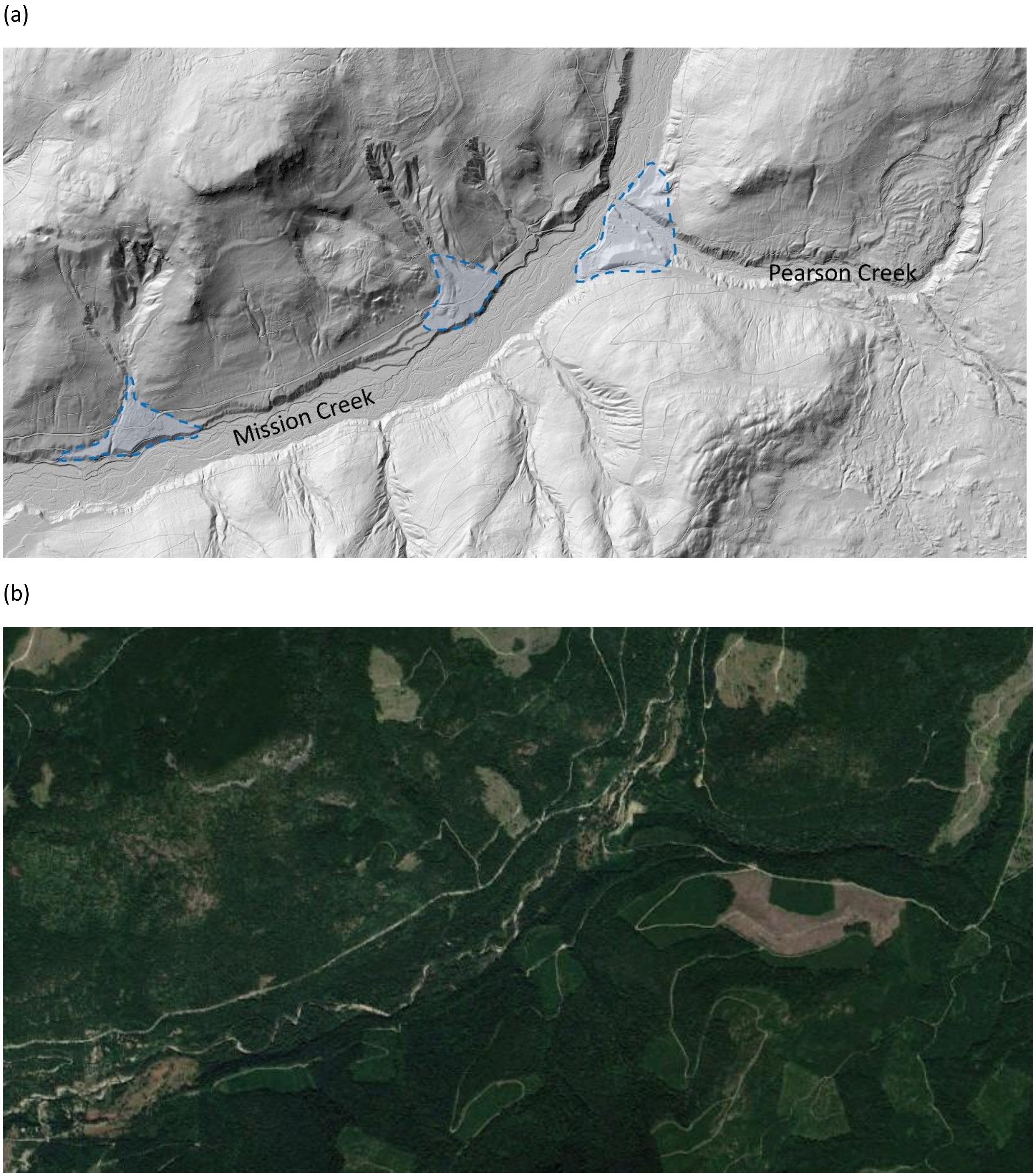

Figure 15: (a) LiDAR Digital Elevation Model of a section of Mission Creek showing alluvial fans emanating from small tributaries as sediment is (was) delivered to the valley floor. (b) Aerial photo image of same location (from Google Earth).

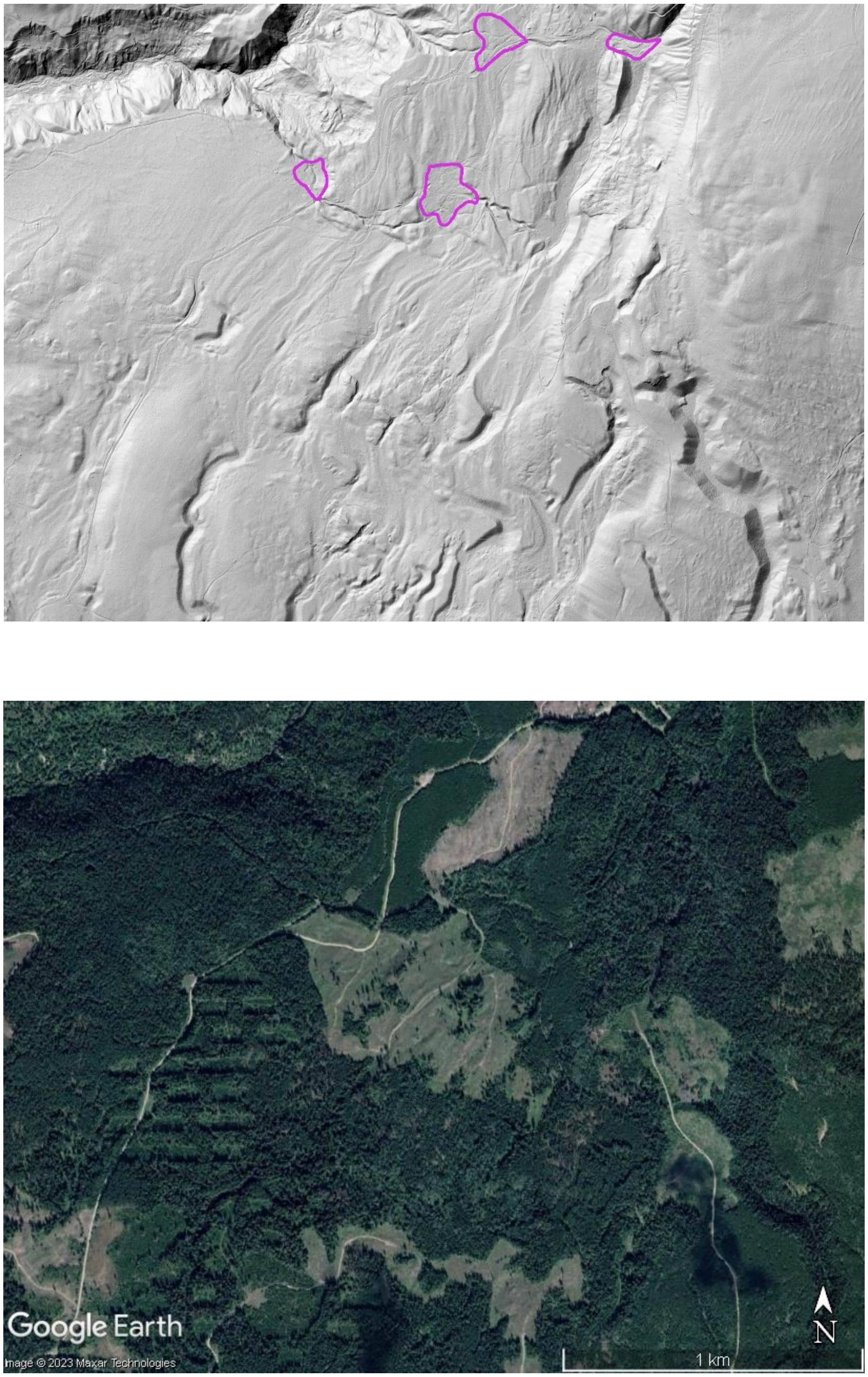

Figure 16: (a) LiDAR Digital Elevation Model of a section of Upper Vernon Creek showing alluvial fans in places where the channel loses confinement. (b) Aerial photo image of same location (from Google Earth).

Mid to high elevation fans are somewhat easier to identify in the field because the channel typically becomes wide and often weaves its way through the forested landscape in a manner similar to a braided channel with "mid channel bars" (Figure 17). The channel bed shows signs of aggradation almost to the level of the banks, which often have wide levees deposited during debris floods. The coarse debris often forces the channel to seek new paths, and there can be extreme turns in the channel geometry. In many respects, these channel reaches have the appearance of an active floodplain rather than an alluvial fan.

Figure 17: Ground view of a section of Upper Vernon Creek (just upstream of the concrete flume section above Ellison Lake) where the channel has lost confinement and an alluvial fan has been deposited. (Photo credit: Bernard Bauer CC BY-NC)

The sediments within mid to high elevation fan deposits rarely make it down to the valley bottom. Hillslope process such as rockfalls, landslides, and snow avalanches can 'load' and fill aggrading channels with sediment (e.g., Woodhurst and de Scally 2018), and these deposits can be mobilized during extremely large floods or debris flow events. Such was the case in Testalinden Creek canyon (Figure 18) after a dam breach in 2010 forced a wave of water to scour the channel of its debris load, which then led to extensive loss of infrastructure on the alluvial fan surface (Tannant 2015).

Figure 18: The failure of a very small dam in the uplands triggered a debris flood that emanated from Testalinden Creek canyon (upper centre of photo) and scoured debris load that had accumulated in the channel for years. (Photo credit: Dwayne Tannant CC BY-NC).

IMPORTANCE of ALLUVIAL FANS

Hydrologic and Hydrogeologic Processes

The hydrologic and hydrogeologic significance of alluvial fans in the Okanagan Basin, especially the large streamflow type fans, is due in large part to their location at the transition from steep mountainous terrain to the flatter valley floor. Streams flow through the apex in distinct channels and spread over the fan surface, leading to infiltration and storage of groundwater in the loose sediments of alluvial fans. However, the complex stratigraphy and depositional history (see Fig 5 and 6) of an alluvial fan greatly influences hydrologic runoff processes on and within fans, especially the potential for surface-groundwater exchange. In combination with climatic conditions and source area characteristics, the morphology of the fan will determine: streamflow rates and persistence across the fan (e.g., perennial versus ephemeral streams); groundwater recharge processes and volumes; the potential for channel entrenchment or avulsion; subsurface flow patterns and susceptibility to contamination; natural water chemistry; and interactions with overlying and adjacent ecosystems (Neton et al. 1994; Woods et al. 2006; Mather et al. 2017).

Surface-Groundwater Interaction and Groundwater Recharge

A stream reach that loses water to the ground via infiltration into the stream bed is referred to as an ‘influent’ or losing stream reach because the water table is below the water level in the stream. Losing reaches may be connected to the water table (if the groundwater level at some point across the stream intersects the streambed) or disconnected (if there is an unsaturated zone between the streambed and the groundwater level) (Figure 19). In both cases, the hydraulic gradient is from higher surface water to lower groundwater. In contrast, when the water table rises above the water level in the stream, the hydraulic gradient is from the bed and banks into the channel, and groundwater supplies water to the stream. In this situation, the stream reach is referred to as an ‘effluent’ or gaining reach, and groundwater contributes to maintaining streamflow. This inflow to the stream can be particularly important during dry periods. If this situation exists throughout the year the stream is classified as perennial. Both losing and gaining situations are common on alluvial fans with a tendency for losing reaches (with losses to groundwater) to occur below the fan apex in the proximal margins of the fan, whereas gaining reaches are generally located farther down-fan at the distal margins. Because of complexities in fan stratigraphy and precipitation seasonality, the intensity of surface-groundwater interactions in losing and gaining stream reaches can change spatially and temporally.

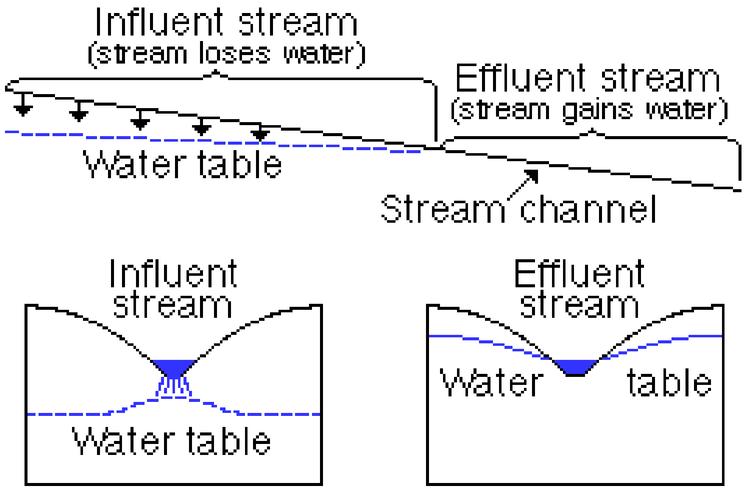

Figure 19: Losing (Influent) versus Gaining (Effluent) streams. From the Kansas Geological Survey, https://www.kgs.ku.edu/General/Geology/Gove/05_gw.html

Influent (losing) reaches on alluvial fans have been found to facilitate underground storage of 20-100% of the discharge delivered by the stream from the drainage basin source area. The exact percentage depends on a range of factors dictated by the characteristics of the fan deposits and the climate, including: sediment properties (e.g., size distribution, sorting, compaction), available aquifer storage, depth to the water table, antecedent soil moisture conditions, the nature of runoff processes contributing to streamflow (e.g., snowmelt, subsurface stormflow, overland flow), losses to evaporation and evapotranspiration, direct precipitation on the channel, and transmission rates of groundwater (Herron and Wilson 2001; Woods et al. 2006). How water flows across the fan surface, whether channelized or as sheet flow, will also affect the active infiltration area, the nature of runoff, and the sediment transport capacity (Herron and Wilson 2001). In general, streamflow that reaches an alluvial fan surface will typically slow and spread laterally because of the gentle slopes below the fan apex, thereby enhancing the potential for infiltration and hence, groundwater recharge of alluvial fan aquifers

The idealised conceptual model of groundwater recharge at the top of the fan assumes that infiltration is focussed near the apex where there are coarser sediments and a lower water table. In the mid to lower fan zones, infiltration may be reduced because of the down-fan particle fining tendencies (described in the section on fan evolution) and because the water table is higher and closer to the stream bed (Blackburn et al. 2021). Recall, however, that this interpretation was derived mostly from studies of streamflow type fans in arid and semi-arid climates, where groundwater recharge rates near the fan apex are greatest (e.g., Blainey and Pelletier 2008; Blackburn et al. 2021), occurring typically during infrequent storm runoff events. The stratigraphy of Okanagan alluvial fans, in contrast, is quite complex owing to the glacial history of the region as well as the mix of contemporary processes that currently modify fan surfaces. It is known, for example, that if debris flow sediments have been deposited regularly near the apex, the greatest recharge rates occur farther down-fan (Bowman 2019). This is because debris flow sediments tend to be poorly sorted with large gravels and cobbles embedded within a matrix of fine particles, which reduces infiltration potential and hydraulic conductivity. In general, infiltration rates tend to be greater where sediments are coarser and well sorted regardless of where this occurs on the fan surface. Infiltration also tend to increase when the water table is lower and during times of enhanced streamflow when the cross-sectional wetted area of the channel is greatest (Houston 2002; Blainey and Pelletier 2008; Bowman 2019).

Infiltration and groundwater recharge are generally most effective when streamflow overtops its banks and spreads out across the fan surface (e.g., during high flow periods or after aggradation of sediments in the main channel) or when the channel becomes very shallow and wide, as is typical on the lower portions of fans. Water is spread over a large surface area, which assists with the infiltration process (Blainey and Pelletier 2008). Some of the water is stored temporarily in surface depressions before infiltrating. These surface depressions may lead to the establishment of new channel positions due to avulsions and normal fan-lobe switching (Neton et al. 1994; Herron and Wilson 2001; Blainey and Pelletier 2008).

The potential for channel avulsions is determined, in part, by the degree of channel entrenchment. On streamflow type fans where stream channels are well established, channel entrenchment is usually deepest at the apex. Channel depth decreases and channel width increases with down-fan distance to the 'intersection point' where the stream is no longer confined to a channel and the flow spills across the fan surface or infiltrates completely. Streams will flow continuously down-fan as long as water supply from the drainage basin exceeds infiltration capacity of the fan sediments. Perennial streams are therefore more likely across fans in humid climates, although continuous streamflow across fans in arid environments is also possible during wet seasons or following large rain events (Blackburn et al. 2021).

Channel entrenchment is enabled by extreme runoff events (e.g., intense rain showers, rain-on-snow events, rapid snowmelt), and such events would be expected to increase with climate warming if rain storms were to become more intense and the volume and frequency of runoff events were to increase (Lecce 1990). Changing surface cover, such as deforestation or conversion of forests to agricultural land, is another factor in determining the future evolution of alluvial fans. Channel entrenchment and avulsion are also related to the supply of sediment from the source area because a greater volume of sediment delivery to the fan implies that stream corridors will be more dynamic as channel aggradation occurs, leading to overbank flooding and the re-positioning of channels across the fan surface (Blainey and Pelletier 2008).

While upstream sediment supply and local erosion determine the basic sediment materials at a location, there is evidence that surface-groundwater interactions can alter the fine sediment composition of existing deposits, thereby altering vertical hydraulic conductivity by several orders of magnitude (Chen et al. 2013). Persistent upwelling of groundwater in combination with the effects of shear velocity in the stream channel can lead to removal of fines from the stream bed. In contrast, downward percolation of water towards groundwater can transport fine sediments into the substrate. These localized processes alter infiltration capacity and hydraulic conductivity of the porous medium, and are therefore superimposed on the broader stratigraphic architecture of a fan.

Subsurface Flow Pathways and Aquifer Storage in Fans

Groundwater flow patterns are controlled by hydraulic head[6] gradients and the hydraulic conductivity patterns of the subsurface sediments (Bowman 2019). As mentioned earlier, the dominance of recharge at or near the apex of the fan implies that the hydraulic head gradient is generally from the apex to distal portions of the fan, both down-fan and laterally. However, there are often local variations in water table heights due to evapotranspiration, well pumping, and preferential flow pathways along unconsolidated coarse sediment layers or subsurface channels and cavities left by burrowing animals and rotting tree-root systems (Neton et al. 1994; Stimson et al. 2001).

While the assumption of down-fan fining of sediment may not always be applicable to Okanagan alluvial fans, it provides a conceptual framework for understanding groundwater storage and movement in fans (Neton et al. 1994). Two conceptual models of down-fan trends in hydraulic conductivity have been proposed: (1) that conductivity and porosity decrease with distance away from the apex (because of down-fan fining), and (2) that conductivity is small near the apex, increases mid-fan then decreases toward the distal portions. The latter is referred to as a “humped trend” of hydraulic conductivity, and is attributed to differences in sediment sorting as the fan evolved (Neton et al. 1994). Sheetflood deposits and mid-channel bar deposits are frequently found at mid fan positions and lower, and these dominantly sandy-gravel sediments tend to be better sorted than at the apex where a mud matrix characterizes debris flow deposits emanating from the supply zone above the apex. Even though sediments near the distal parts of the fan are typically finer than elsewhere on the fan, they are also well sorted and can have larger hydraulic conductivities because of their open grain-packing structure and inter-pore connectivity (Neton et al. 1994). Which model best describes a particular fan depends on the depositional history of that fan, and this is controlled by the geology and topography of the source area and general hydro-climatic conditions.

It is well known that hydraulic conductivity in the stratigraphy of alluvial fans is anisotropic, meaning that its value changes depending on which of the three cardinal directions one is concerned with (down-fan, laterally, vertically). This directional heterogeneity of the sediments will affect groundwater flow pathways as well as aquifer productivity. For example, because of the vertical layering of fan sediments in discontinuous lenses, hydraulic conductivity in the vertical direction tends to be orders of magnitude less than in the horizontal direction within a given aquifer (Neton et al. 1994; Houston 2002). Clay lenses in particular serve as aquitards[7] preventing significant vertical migration of water locally. Aquifer yields tend to be greatest near the apex of streamflow-type fans, where sediments are coarser and more

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[6] Groundwater head represents the total potential energy of groundwater that allows it to flow, and is expressed in units of metres of water. The groundwater head is composed of the elevation of the water, representing potential energy due to gravity, combined with the pressure the water is under, representing potential energy due to that pressure. Water at the water table is under no pressure (relative to the air), and the water table elevation is equal to the groundwater head of the water. For water that is below the water table, groundwater head has both elevation and pressure components. It can be measured by installing a well and allowing the water to rise in the well. When the well fills, and no water is moving in or out of the well, then the total groundwater head of the groundwater outside the well screen will be equal to the total groundwater head of the water everywhere inside the well. The elevation of the top surface of the water inside a well (where the water is not under pressure relative to air) can be used to measure the total groundwater head of the water at the bottom of the well (where the water is lower, and under pressure).

[7] An aquitard is sediment layer with a much lower hydraulic conductivity than adjacent materials. Aquitards in unconsolidated sediments tend to be clays and silts.

permeable (Blackburn et al. 2021). Decreased productivity values are found in distal portions of fans, attributed mostly to thin stratigraphic beds (Bowman 2019; Blackburn et al. 2021).

The layering of coarse and fine (aquitard) layers near the toe of fans (Fig. 5, 6) can lead to unique groundwater conditions near the base of some fans. Water leaves the stream at higher elevation portions of the fan, thus starting its flow across the fan with higher groundwater head. As indicated, groundwater may be flowing into streams near the base of the fan (Fig. 19). In certain fans, this can mean that the groundwater head at deeper depths is higher than the groundwater head near surface. Artesian conditions are encountered when the groundwater head at depth is greater the elevation of the ground surface. Artesian groundwater conditions require specific well drilling methods to be used for safe installation of groundwater wells, otherwise it can result in the uncontrolled flow of groundwater from depth to surface both inside and outside the well. Flowing artesian wells can be very costly to bring under control.

Modeling of fan hydrogeology is very complex and uncertain. The simplest numerical models treat the fan as a single homogeneous system, which is not unreasonable if aquitards are discontinuous and of limited extent and if there is a high degree of interconnectivity between water-bearing layers (Stimson et al. 2001; Bowman 2019). Differences in groundwater geochemistry across the fan aquifer would be negligible. More complex models attempt to characterize the dominant aquifers and flow pathways, but this requires extensive knowledge of subsurface stratigraphy, usually obtained through costly drilling programs and remote sensing techniques (e.g., ground penetrating radar). Zhu et al. (2017) identified three zones radiating from the apex of a fan in China, and assigned values for hydraulic properties based on geophysical data for deposits in each zone. In their case, poorly sorted, highly variable and high conductivity deposits in the apex zone transitioned to better sorted sediments in the mid-fan zone. However, some fan aquifers must be represented as more complex systems. For example, Weissmann et al. (2002) used deterministic models for large scale features and stochastic methods to represent intermediate scale heterogeneity. Their approach allows for representation of facies that formed under different depositional conditions, but it is an expensive and time-consuming undertaking.

Land subsidence

Groundwater in aquifers is under pressure, and this pore water pressure exerts an outward and upward force on the sediments that make up the aquifer. As a consequence, the volume of pore spaces and separation distances between particles are maintained as long as the hydraulic head within the groundwater system is sustained. Extraction of groundwater or prolonged periods of drought can lead to dewatering of pore spaces, lowering of the groundwater head, and subsequent collapse of the pore volume. Such internal compaction manifests itself at the surface as subsidence or a widespread sinking of the land. Fine-grained clays and highly compressible flaky sand-sized sediments from slate and shale bedrock sources are particularly susceptible to compaction (Liu et al. 2004; Bowman 2019). Land subsidence affects infrastructure, which is a potential concern in the Okanagan in locations where extensive development (e.g., housing, roads, railways, sewers) has taken place on the fan surface, and results in an overall loss of aquifer storage potential and groundwater transmissivity.

Prediction of subsidence is challenging because the stratigraphy of alluvial fans is complex. In a study of a heavily developed alluvial fan complex in China experiencing subsidence, Lu et al. (2020) found that subsidence began in the distal parts of the fan, but over time also began to occur toward the mid fan area. Changes to groundwater extraction have slowed the subsidence rate in parts of the fan, but substantial subsidence rates of 3.5-6.7 mm/y continue in others. In general, subsidence is considered to be irreversible once the pore spaces have been compacted, but there is evidence that subsidence due to seasonal fluctuations in groundwater levels is partly recoverable (Liu et al. 2004). There appears to be a trade-off between changes in pore space volume due to water content and mass loading induced by changes in groundwater storage. A decrease in groundwater level will evacuate some pore spaces leading to some degree of compaction, but the reduced mass loading implies less overall weight on the sediment column, yielding net expansion and slight uplift of the surface. The details clearly depend on the internal architecture of the fan deposits and their water-holding characteristics.

Ecosystem Resilience and Environmental Flows

The movement of water over and through alluvial fans is of relevance not only to human water resources concerns but also to the sustenance and resilience of terrestrial and aquatic ecosystems such as forests, wetlands, riparian areas, and instream communities of invertebrates and fish. Greater infiltration and lower water tables near the apex imply the need for deep root systems to take advantage of stored water. In contrast, higher water tables and lower hydraulic head gradients near the toe of the fan are favourable for the development of springs, saturated sediments, marshes and wetland ecosystems (Bowman 2019) and for maintaining streamflow. Seasonal variability in water supply to down-fan ecosystems correlates well with variability in groundwater recharge processes in the upper fan areas (Woods et al. 2006) during precipitation events and spring freshet in snowmelt dominated regions. In general, water storage in alluvial fan aquifers provides significant buffering capacity for water delivery to downstream ecosystems (Herron and Wilson 2001; Woods et al. 2006), including those directly on the fan and those farther away. However, some ecosystems adjacent to fans may be hydraulically disconnected from the fan aquifer (Petalas 2013) and totally isolated from the hydrologic runoff processes that dominate the fan. There is a need to better understand how the size and distribution of alluvial fans in a watershed can affect runoff and sediment delivery downstream and in main river valley corridors (Herron and Wilson 2001; Neton et al. 1994; Mather et al. 2017).

There has been increasing attention paid to the importance of Environmental Flow Needs (EFNs) and Critical Environmental Flow Thresholds (CEFT) to sustain aquatic ecosystems and fish habitat due to their explicit inclusion in the BC *Water Sustainability Act* of 2014. This issue is inextricably linked to alluvial fans, as many Okanagan tributaries flow across alluvial fans before discharging into the mainstem, either Okanagan Lake or the Okanagan River. As indicated, the flow across fans varies considerably under natural conditions including: perennial streams with consistent flows; perennial streams with significant losing and gaining reaches; perennial streams at the head of the fan that may be entirely absorbed before reaching the fan toe; ephemeral streams that flow from head to toe when active; and finally, ephemeral streams that may not reach the toe even when active. Continuous streamflows across fans are essential for fish to access spawning and rearing habitat throughout the year. In the Okanagan, critical times for fish passage align with natural low flow and precipitation periods and, in the summer and early fall, irrigation demand. Habitat loss and barriers to fish migration result from extremely low flows or completely dry sections of tributaries.

The Okanagan Environmental Flow Needs Project was initiated by the Okanagan Nation Alliance (ONA), the BC Ministry of Forests (MoF), and the Okanagan Basin Water Board (OBWB). EFNs and CEFTs were developed for 18 streams identified as a priority for all groups involved for select fish species at critical times (ONA 2020). These metrics were developed using either the Okanagan Tennant (desktop-based) or Okanagan Weighted Useable Width (field-based) methods specifically designed by the project team for application to the Okanagan environment. Additional field information collected identified channelization, water diversions, and loss of riparian vegetation as contributing to the degraded nature of tributaries that cross alluvial fans in the Okanagan. Channelization alters stream length and hence water velocity, which leads to downcutting of streams and disconnection from adjacent riparian habitats. Water temperatures are known to regularly exceed suitable temperatures for salmonids in flowing reaches and disconnected pools, which is a function of both lower flows and the loss of riparian habitat as documented in many Okanagan tributaries (OBMEP 2022).

Due to a lack of existing hydrometric data, streamflow estimates were required to support the setting of EFNs. Associated Environmental Consultants Inc. (2019) estimated streamflows at each fan apex, and then adjusted for streamflow losses or gains across the alluvial fan based on limited field measurements collected by ONA or values determined as part of the Okanagan Water Supply and Demand Project (Summit Environmental Consultants Ltd. 2009). The fan loss or gain values applied by Associated Environmental Consultants Inc. (2019) were either 0 or a fixed value, due to the limited information available. As a result, one of the recommendations from the EFN project was to further assess and refine the spatial and temporal variability in groundwater – stream exchange on alluvial fans to support development and implementation of EFNs and CEFTs (ONA 2020).

The regulated nature of the Okanagan system and extreme flow events can also affect fish access to tributaries on alluvial fans. For example, the water level in Okanagan Lake is only allowed to vary within a small range, which limits the formation of perched fan/deltas as seen for example in Arrow Lakes. However, in 2017, the Okanagan Lake level was high during spring freshet, which led to gravel build up in Shorts and Equesis Creeks, blocking fish access to upstream habitat until it was removed. Figure 20 shows the evolution of a barrier bar at the mouth of Shorts Creek over a 10-year period due to sediment supply from the creek and longshore drift to the north by wave action and longshore currents. The blockage of the creek mouth to fish access is clearly evident in the 2016 photo. Alluvial fans do not appear to be specifically targeted by shorespawning kokanee in the Okanagan. Mapping of the distribution of shorespawners is currently underway (ONA and MoF).

Figure 20: Gradual development of a barrier bar at the mouth of Shorts Creek (Fintry fan-delta) restricting fish access to the creek. Images from Google Earth.

HAZARDS and RISKS on ALLUVIAL FANS

‘Hazard’ refers to a potential source of damage or harm should an event come to pass. Common sources of landscape-based hazard include mass movements, floods, storms, and wildfires. ‘Risk’, on the other hand, refers to the likelihood that some degree of harm may occur, which involves evaluating the chances that an event hazard will occur as well as the extent to which there is exposure to a hazard with the possibility of financial loss or personal injury. Risk on alluvial fans is therefore a function of: (1) the nature and location of elements such as people, roads, private land and structures; (2) the suite of hydrogeomorphic process placing those elements at risk; and (3) the vulnerability of those elements to the dominant processes. Clearly, there can be no risk on fans unless there are elements on fans that are susceptible to a natural hazard. In the absence of such elements at risk, alluvial fans are simply areas that function to regulate the movement of water, sediment, and debris thereby dissipating energy naturally. In such a natural landscape untouched by human activity, mass movements and floods do not pose a risk to society.

Unfortunately, alluvial fans are frequently viewed as favourable sites for development, forestry, and aggregate mining, whereas they should be viewed circumspectly as places where large fluxes of energy and matter (water and sediment) are concentrated. Sufficiently intense hydrometeorological events can turn what appears to be an inactive fan area into a hazardous environment within a very short period of time. Avoidance of all infrastructure development on active fans is the preferred approach rather than devising ways to mitigate current and future risk that may be created by human occupation of fans. In British Columbia, risks associated with construction on alluvial fans have received increasing attention from both research and regulatory perspectives since the early 1980s, following events that resulted in fatalities along Highway 99 between Horseshoe Bay and Squamish, and later Hummingbird Creek on Mara Lake in 1997. As a result, a sound understanding of the principles and processes of evaluating fan hazards in BC already exists (e.g. Hungr et al. 1984; VanDine 1984; Hungr et al. 1987; Jackson 1987; Kellerhals and Church 1990; Wilford et al. 2009; Glade 2005; Huebl and Fiebiger 2005; Jakob 2005; Welsh and Davies 2011).

A five-step assessment process proposed by Wilford et al (2009) can be used to understand current and potential risk on alluvial fans along with possible mitigation opportunities at both the site and watershed level. Steps include:

1. Identify fans and delineate watersheds.
2. Identify elements at risk on fans.
3. Investigate fan processes.
4. Investigate watershed processes.
5. Analyze risks and develop plans.

1. Identify fans and delineate watersheds

Alluvial fans can be identified broadly by using a simple definition that states that fans occur everywhere that a stream channel loses confinement. Supplemental information from contour mapping and bare Earth imagery generated from LiDAR-based data can assist in this regard (see Figures 15 and 16). Larger fans, typically at low elevation, can be clearly seen on such bare Earth maps, which are available for most of the valley bottom in the Okanagan Valley (accessible at https://governmentofbc.maps.arcgis.com/apps/MapSeries/index.html?appid=d06b37979b0c4709b7fcf2a1ed458e03). Smaller features at mid to high elevation may not be obvious from such bare Earth images and they must be identified and mapped using field reconnaissance. Watersheds that contribute flow, sediment and debris to alluvial fans can be delineated using publicly available TRIM mapping, augmented by Google Earth or Bing satellite imagery and LiDAR-based elevation information where available.

The delineation of watersheds that drain to alluvial fans is important because land use activity within the watershed has the potential to affect the volume and timing of flows that reach the fan along with the volume of sediment and debris carried by streamflow, debris floods and debris flows. Alluvial fans that occur at mid to high elevation can make watershed delineation for low elevation fans difficult because flows that diverge at higher elevations can drain down to more than one fan at lower elevation. Gentle over steep (GOS) environments are characterized by relatively gentle terrain overlying or overlooking steeper terrain (Grainger 2002). Diversion of natural drainage on the gentle portion of GOS configurations can occur as a result of forestry activities and other development, often with serious impacts on steeper slopes below.

2. Identify elements at risk on fans

The identification of elements at risk on fans must include not only a description of the element(s) but also consideration of the area around the location of the element with respect to fan processes (defined below), and the vulnerability of each element to the dominant hydrogeomorphic process – flooding, debris flooding, and debris flows. Elements potentially at risk on alluvial fans vary depending on fan location, with generally high-value elements such as people, private holdings, public transportation infrastructure, water intakes, etc. situated on low elevation fans. Fans at mid to high elevation generally have lower-value elements, but can be equally important because destabilization of mid elevation fans, for example, can affect steep terrain upstream of low elevation fans where high-value elements occur. Mid to high elevation fans are generally located on public lands where forest management and other resource management activities occur. As such, the location and design of resource roads, the nature and extent of forest harvesting activities, and the location and type of resource extraction (e.g., gravel pits) are important considerations.

Okanagan fans occur at many elevations in the watershed, and consequently, all features should be mapped and at-risk elements identified such that connections between upslope and downslope hazards can be made. An example is the possibility of landslide or debris flow activity that terminates on a mid-elevation fan, which provides a buffer for the areas at lower elevations, resulting in a lower risk there. On the other hand, changes on mid elevation fans, such as channelization or stream re-routing that allow hydrogeomorphic events to continue through to lower elevations can raise the risk on fans in those areas. This is sometimes referred to as “transfer of risk” and it can occur at the watershed and site scales.

The location of elements potentially at risk relative to inactive benches or relict areas on fans should also be mapped and recorded. Relict features are those that were formed under a different hydrogeomorphic environment than the present, usually because of changing climatic conditions (e.g., glaciation) or shifts in the hydrologic regime leading to different vegetation cover and runoff properties.

3. Investigate fan processes

In British Columbia, the forestry sector generally recognizes three principal hydrogeomorphic processes that influence fans – flooding, debris flooding, and debris flows – and affect risk. All three processes can be active on a fan, although there is often one dominant process. The investigation of these fan processes can be complicated by land uses that obscure evidence of historic processes that may have created the fan and contemporary processes that are responsible for continued evolution or modification of the fan. In addition, the dominant process(es) can change with distance downstream from the fan apex, and it is not unusual for debris flows to transition into debris floods and later sediment laden floods, depending on fan size. Debris flows are typically the most destructive type of event on alluvial fans, and as such, most of the effort that is applied as part of a risk analysis is focused on the potential for debris flows to reach the fan as well as the extent of possible debris flow deposition over the fan surface. Of course, debris floods and flooding can also cause significant damage to land and structures on alluvial fans through erosion and deposition or avulsion (change in channel course).

The fan apex is generally the most hazardous place for development of any kind, for two reasons:

1. The apex is the narrow point through which all water and sediment delivery must pass. The farther downstream an at-risk element is from the fan apex, generally the less likely that it will be affected by an event or process.
2. Debris flows transition into debris floods and sediment laden floods as a function of event size and distance downstream from the fan apex, and in general, the available energy decreases.

It is critical to determine the most likely and effective hydrogeomorphic process (or suite of processes) at various locations on a fan in order to assess the exposure and vulnerability of at-risk elements. It is also essential to determine the return interval of each process identified such that development-related decisions can be made. Peak discharge during debris flow events can be orders of magnitude greater than flood events and as such can do much more physical damage. Debris flows also pose significant risk to public safety where people are present. Field indicators are best used to determine dominant hydrogeomorphic processes including the presence of boulder levees and boulder lobes left behind by debris flows, sediment splays created during debris flood events, and overbank sediment and debris deposition that occurs during flood events. The internal sedimentary architecture of fan deposits is also very useful in differentiating between debris flows and floods, when exposed banks or road cuts pass through the fan surface.

In addition to field indicators, there are several basin and fan morphometric measures that can be used to understand dominant hydrogeomorphic processes. The use of morphometric variables for this purpose has been demonstrated in a variety of mountain regions (e.g. Kostaschuk et al. 1986; Jackson et al. 1987; Jakob and Bovis 1996; Calvache et al. 1997; de Scally et al. 2001; de Scally and Owens 2004; Wilford et al. 2004; Kovanen and Slaymaker 2008; de Scally et al. 2010), with the potential for at least some of the morphometric measures to be derived within a Geospatial Information System (GIS) (Rowbotham et al. 2005).

The most common basin measures are those related either directly (e.g. Melton's ratio, relief ratio) or indirectly (e.g. basin area, basin stream length) to the steepness or gradient of the basin, because a sufficiently steep gradient is required to evacuate debris flows from the contributing channel, through the fan apex, and onto the fan surface. Useful fan measures are typically some aspect of the fan gradient (e.g. average gradient along the fan axis), because a sufficiently steep gradient is required for debris flows to be able to maintain momentum on the fan.

The Melton Ratio (R) is commonly used, and it takes the following form:

$$\mathrm{R} = RR/(A_d)^{0.5}$$

where RR is relative relief (difference between highest and lowest points in the drainage basin) and A_d is drainage area. Church and Jakob (2020) assembled published values of the Melton Ratio and plotted them against watershed stream length (length of mainstem channel), as shown in Figure 21.

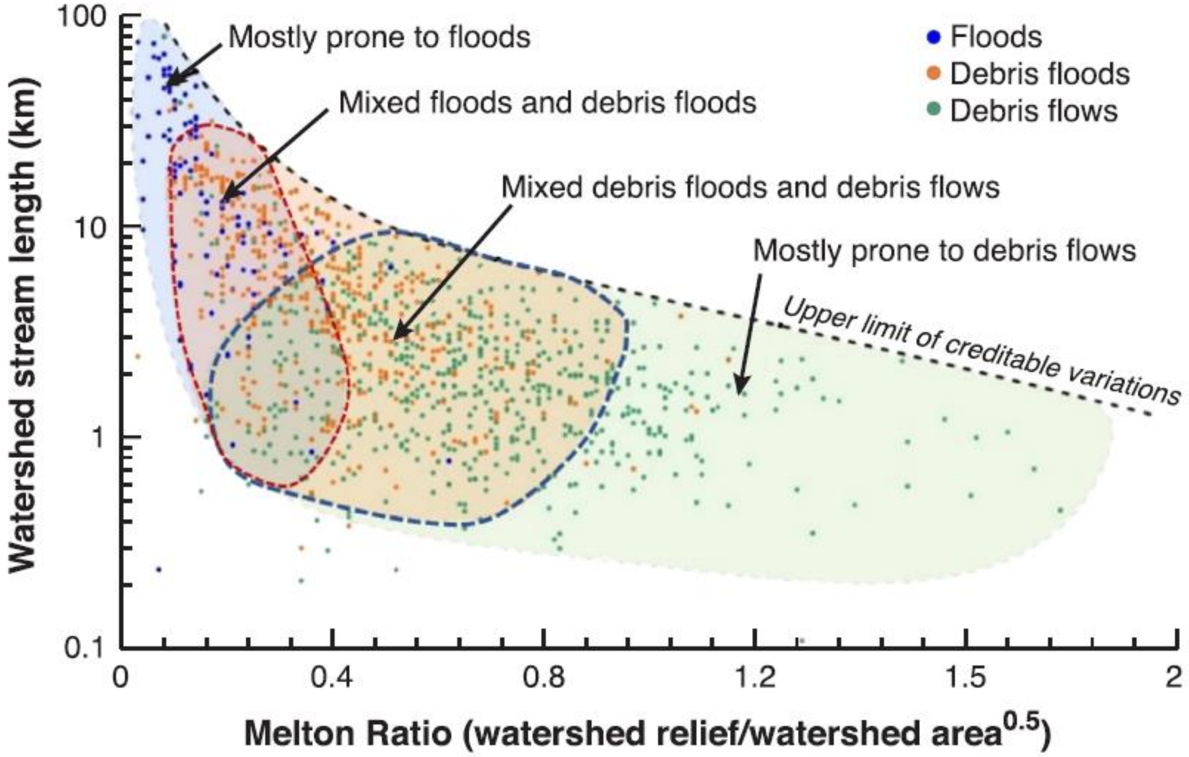

Figure 21: A plot of Melton Ratio against watershed stream length indicates that different alluvial fan processes occur in different areas of the plot, as shown by clustering of alike values. Steeper, heavily incised terrain with short channel lengths are subject to debris flows whereas flatter terrain with long channel lengths tend to be dominated by floods (From Church and Jakob 2020).

The history of debris flows on a fan is more difficult to discern than that of floods; while the recurrence interval of floods is typically measured in years, the recurrence interval of debris flows is typically measured in decades or centuries. This makes the identification of old debris flow deposits difficult, especially in wetter environments where rapid vegetation growth can obscure geomorphic evidence. Also, flood events on a channel subsequent to a debris-flow event can modify or remove much of the debris-flow evidence. Where old debris flow activity is suspected, fan-wide and detailed hazard analysis may be required.

The success of any morphometric approach for evaluating hydrogeomorphic hazards is dependent on there being a sufficiently clear demarcation in the thresholds of the chosen morphometric measures, between basins capable of delivering only floods to their fan and those also capable of delivering debris flows onto the fan (see Figure 21). There are several challenges with respect to these thresholds:

a) Fans whose basin-fan morphometric measures lie in the transition zone between fluvial and debris-flow fans require further careful evaluation. A cautionary tale is provided by Five Mile Creek near Banff: it experienced a large debris flow in 1999 (de Scally et al. 2003; 2004), despite the fan gradient being at the threshold between fluvial and debris flow fans for this part of the Rocky Mountains, and the fan surface showing no evidence of modern debris flow activity (de

Scally 1999). The critical factors in the 1999 event were a basin whose Melton Ratio was well above the threshold required for debris flows to reach the fan, an abundant sediment supply in the basin, and a triggering rain storm of unusual intensity (Thurber Engineering 2002).

b) The threshold between flood prone and debris flow prone fans may vary in different environments. For example, in the Southern Alps of New Zealand, the thresholds for the Melton Ratio and average gradient of the fan axis are both markedly higher in the greywacke (sedimentary rock) mountain ranges compared to the schist (metamorphic rock) mountain ranges (de Scally and Owens 2004; de Scally et al. 2010).

c) Sediment storage traps within a basin may invalidate many of the basin's morphometric thresholds, because even if the basin is sufficiently steep for debris flow activity to reach the fan, these events may terminate in the trap. Such sediment traps can include mid elevation fans created by stepped valley profiles (Jackson et al. 1987) and relict cirques[8] (de Scally and Owens 2004) as well as human-constructed debris catchment reservoirs.

If the potential for debris flows to reach an alluvial fan is suspected from a morphometric analysis, then detailed field investigation is required to determine whether debris flows have historically reached the fan. The fundamental question that needs answering is "is there evidence that debris flows have in the past extended downstream of the fan apex?" This involves a search for evidence such as boulder levees adjacent to channels, boulder lobes, large boulders deposited on the fan surface, diagnostic sedimentary architecture in exposures along the channel banks, and bark damage on trees adjacent to channels. The entire fan surface should, in theory, be searched not just the fan adjacent to the modern active channel. Typically, the probability of finding evidence of debris flows increases up-fan toward the apex. Old air photos are useful for identifying and mapping old channels on the fan as are LiDAR digital elevation models (DEMs).

The above method relies on the identification of historic debris flows to determine whether these events can reach a fan; this is problematic if the evidence of debris flows is scarce, been removed by subsequent fluvial action, is hidden by vegetation growth, or has been modified by land-use activities. An analysis of the sediment sources available in the basin for future debris flows may be necessary, combined with a comparison of the basin with the characteristics of nearby basins known to produce debris flows. This methodology has been used, for example, along highways in BC (e.g. Thurber Consultants Ltd. 1983a; 1985). Sediment supply conditions in basins have been found to be important for predicting debris flow activity (Bovis and Jakob 1999).

In geosciences practice and engineering practice in many parts of the world there is an increasing demand for quantitative debris flow hazard analysis (Jakob 2005). These are complex and costly exercises, involving a wide range of specialised expertise, and usually limited in some fashion by data availability. Jacob (2005) provides a comprehensive review of this topic.

4. Investigate watershed processes

As described in the previous section, fan investigations using digital imagery and field methods provide an understanding of past hydrogeomorphic processes that formed the fan as well as contemporary processes that are active on fans. However, an assessment of the watershed above the fan is also

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[8] A cirque is a small, circular or amphitheater-shaped valley created in the former location of a small glacier.

critically important to understand how hydrologic and geomorphic processes, as well as human activities, are linked to the processes observed on the fan itself. These interconnections provide an understanding of potential risk, and possible trigger mechanisms that may generate hazards in the future.

Where flooding is the dominant hydrogeomorphic process on an alluvial fan, there are two causes to consider: (1) intense rainfall or snowmelt generated runoff, especially rain-on-snow events; and (2) release of stored water from natural or human-constructed reservoirs, ponds, and lakes. Where a watershed is mostly forested, reductions in forest cover due to wildfire, forest harvesting, or other form of land clearing can increase snow accumulation and snow melt rate resulting in increases in flood frequency and magnitude. Resource road construction can increase drainage density through the diversion and concentration of surface and sub-surface runoff, also contributing to an increase in flood frequency and magnitude. Where extensive lake and wetland features occur, runoff and flood frequency can be attenuated through natural storage and release. The release of stored water from features such as beaver dams and reservoirs can also trigger flood events down onto fans as witnessed on Testalinden Creek in 2010 (Tannant 2015). Reservoirs of sufficient size relative to watershed areas, when managed for flood relief, can help to mitigate flood hazard on alluvial fans.

Debris flood frequency can also be increased through increases in snow accumulation and snow melt rate that increase flood flow levels, but also through increases in stream sedimentation from upslope erosion and landslide events. Watersheds characterized by steep slopes coupled to lower-gradient mainstem and tributary channels can be prone to debris loading by land-use activity that affects natural drainage patterns, particularly on gentle terrain overlying or overlooking steeper terrain (GOS).

Debris flows are most often triggered by landslides that impact on steeper mainstem channels; the landslide transitions rapidly into a debris flow and maintains momentum as a function of streamflow volume at the time of occurrence, the volume of sediment and debris involved, the angle of incidence, and stream gradient. Debris flows can also be initiated in-stream during high-flow periods where sufficient volumes of material are involved and combined with steeper-gradient channels. Land use activity can affect the frequency of landslides, particularly where effects on natural drainage occur, and streamflow levels required for instream initiation of debris flows can be affected by reductions in forest cover, drainage diversion and concentration by roads, and unplanned release of stored water from reservoirs.

Re-routing of natural water runoff pathways on fans as a result of forest road construction has resulted in serious water-related issues in downslope and downstream areas. Diversions of natural drainage off of alluvial fans in gentle-over-steep transitions often result in landslides into mainstem and tributary channels that either continue as debris flows to the terminal fan, or load the channel for subsequent release during high flow events that can cause debris flooding under certain circumstances.

5. Analyze risk and develop plans

Risk as defined by Wise et al. (2004) is a measure of the probability of a specific event occurring and the consequence, or adverse effects, of that event on specific elements, such as human health, property, or the environment. Once the elements potentially at risk on an alluvial fan have been identified along with the dominant hydrogeomorphic process in those locations where elements are potentially at risk, a risk analysis can be undertaken and steps to mitigate risk can be considered. The process can also be applied where some form of development is planned that could put elements at risk, but development has not yet occurred.

Where risk is determined to be moderate or high, some form of mitigation should be applied, and avoidance should always be an option. As mentioned above, where there are no elements at risk on alluvial fans, there is no risk. Where development of some sort either exists on a hazardous alluvial fan, or must occur for one or more reasons, strategies to address both the hazard and consequence side of the equation can be applied. Where flooding is a concern, water storage in reservoirs at higher elevation can be considered provided that flood management is a requirement of the installation. Where drainage diversion by roads during flood events may occur, rolling grades can be used along with short term or maintainable structures. Where debris flows are expected avoidance is often the best management practice, otherwise containment, diversion or some other form of protection structures maybe required. Unfortunately, most of these mitigation strategies involving engineered structures tend to be quite expensive, which points to the distinct advantages of avoiding development on alluvial fans.

STUDIES of ALLUVIAL FANS in the OKANAGAN

There have been a large number of studies investigating alluvial fans in BC with respect to hazard potential from geotechnical failures and flooding (e.g., Kellerhals and Church 1990; Jakob and Bovis 1996; Wilford et al. 2004; Wilford et al. 2005a;b; Wilford et al. 2009; Millard et al. 2006; Nicol et al. 2013). In addition, there have been investigations (e.g., Jakob et al. 2000) into alluvial fan processes following major events in the North Okanagan and Shuswap region (e.g., Rogers Creek, Hummingbird Creek, and Sicamous Creek). The findings are relevant to alluvial fans in the Okanagan, but the context is slightly different given the more arid conditions, especially in the BC Southern Interior.

Several studies have been undertaken on some of the major alluvial fans in the Okanagan, which are judged to be of major importance to fisheries management. Associated Environmental Consultants Inc. (2019) specifically mapped 18 alluvial fans of the major tributaries investigated to establish EFNs (see Ecosystem Resilience and Environmental Flows section). Figure 22 shows the location of these mapped fans in association with the primary aquifers in the region. Each of the fans is underlain, at least partially, by an aquifer, and therefore it is important to better understand the hydrogeological conditions on alluvial fans, particularly groundwater-surface water exchange processes.

As part of the Okanagan Water Supply and Demand Project, Summit Environmental Consultants Ltd. (2009) found limited research on streamflow losses or gains for Okanagan tributary streams that flow across alluvial aquifers (fans). However, using the findings by Lowen and Letvak (1981) and Obedkoff (1990), Summit Environmental Consultants Ltd. (2009) estimated streamflow losses or grains across 32 of the main Okanagan tributary streams (Appendix 1). Summit Environmental Consultants Ltd. (2009) also recommended that further detailed field based hydrologic and hydrogeologic investigations were required to increase the understanding of the spatial and temporal variability of streamflow losses across alluvial fans in the Okanagan Basin.

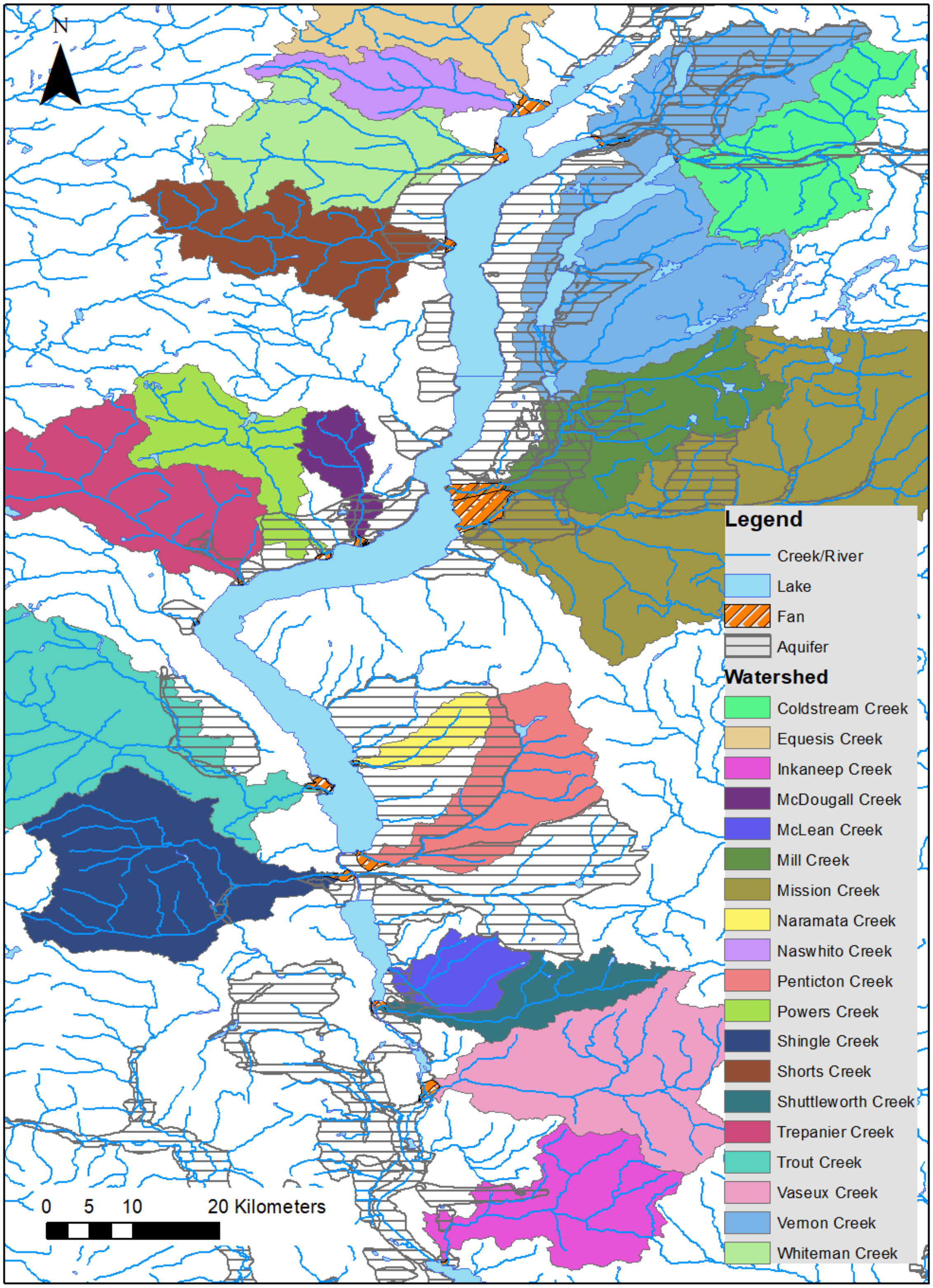

Figure 22: Distribution of streams, alluvial fans and mapped aquifers throughout the Okanagan Valley as assessed in ONA (2020). Data sources: watershed and fan layers (Associated Environmental Consultants Inc. 2019); aquifers (BC Data Catalogue). Adapted from Welch and Montgomery (2022).

To provide insight into alluvial fan hydrologic processes, the ONA and OBWB commenced a multi-phase project to assess the utility of multiple techniques to assess groundwater-surface water exchange processes on several of the alluvial fans in the Okanagan Basin shown in Figure 22. The project was designed to evaluate various methods that can identify the spatial and temporal variability in hydraulic connectivity, source waters, and water exchange between the surface and subsurface. Techniques included co-located surface water and groundwater monitoring stations across the fan, and hydrometric, hydraulic and environmental tracer analysis. Shingle Creek was selected as a demonstration creek due to its high fisheries value (Welch and Montgomery 2022). The techniques have also been applied in partnership with Westbank First Nation (WFN) for McDougall Creek and the BC Ministry of Forests (MoF) for Vaseux Creek. While these projects are on-going, the key finding from a methods perspective is that a combination of hydrometric, hydraulic, and environmental tracer techniques over several years is required to untangle the complexity of surface–groundwater exchange on alluvial fans. Preliminary findings for each of these creeks follows, together with summaries of other studies undertaken on fans in the Okanagan.

Shingle Creek – Shingle Creek flows out of a bedrock canyon and east across an alluvial fan before joining Okanagan River in the channelized section at Penticton. Shingle Creek historically meandered across the alluvial fan, but is currently channelized and confined to the northern margin of the fan. The Shingle Creek alluvial fan likely formed during several glacial and fluvial episodes as it consists of multiple aquifers separated by confining clay layers (Summit Environmental Consultants Ltd. 2007). These layers do not, however, appear to be continuous across the fan, and as a result, groundwater flow within the Shingle aquifer is complex. Distinct groundwater – stream exchange was identified in two reaches (Welch and Montgomery 2022). Reach 1, from the apex to mid fan, appeared to be neutral, neither gaining nor losing water. Co-located groundwater monitoring data suggests that at least in some areas the stream is disconnected from the underlying shallow groundwater. Reach 2, from the mid fan to the mouth oscillated between gaining and losing depending on season and likely Okanagan River level. Despite a lack of measurable stream loss, underlying aquifers appeared to be recharged by water from Shingle Creek, sourced either from snowmelt and/or precipitation at higher elevations. The creek did not dry up during the two years of monitoring, which may be partially attributed to the presence of a mid-elevation aquifer located above the canyon (AQ266) and spring discharges in the canyon. On-going work is assessing the relationships between actual and potential fish habitat, riparian vegetation, and surface water – groundwater exchange on the fan.

Vaseux Creek – Vaseux Creek flows west out of a bedrock canyon and across its alluvial fan before joining the Okanagan River north of Gallagher Lake. The alluvial fan merges with floodplain deposits of the Okanagan River. Vaseux Creek has been channelized for the lower half of the alluvial fan. Distinct groundwater – stream exchange was identified in three reaches. Reach 1, from the apex to braided section, appeared to be neutral, neither gaining nor losing water. However, there are two licensed diversions along the reach that remove water for different water use purposes. The percentage of water diverted from the creek varied throughout the year, but increased at lower flows. Reach 2, the central reach where the creek braids, exhibited the greatest loss of water in all seasons. The northern braid consistently dried up during periods of low flow. Reach 3, the channelized portion of the creek that is deeply incised, oscillated between gaining and losing, depending on streamflow, season, and the Okanagan River level. Vaseux Creek dried up in Reach 3 before reaching the Okanagan River in both years of monitoring, creating a barrier to fish passage. The underlying aquifer (Aquifer ID 255) appeared to be recharged by both Vaseux Creek and the Okanagan River. The identification of water source was aided by the contrasting isotopic (^{2}H-H_2O and ^{18}O-H_2O) values of Vaseux Creek (sourced from higher elevation precipitation and/or snowmelt) and the Okanagan River. On-going work is assessing the relationships between actual and potential fish habitat, riparian vegetation, and surface water – groundwater exchange on the fan.

McDougall Creek – McDougall Creek flows eastward out of a bedrock canyon before crossing glacial outwash deposits, descending through a deep gully bounded by Mt. Boucherie, and finally crossing an alluvial fan before reaching Okanagan Lake. Groundwater – stream exchange appeared to be governed by geology and water diversions. The greatest loss and rate of loss of water from the creek occurred where it flowed across the glacial outwash deposits. In recent times, this stretch has often been observed to dry up in the summer (ONA 2020; 2022), creating a barrier to fish migration and loss of instream habitat. Water was also consistently lost from McDougall Creek as it crossed the alluvial fan at the valley bottom. Flows were observed to be low, but not dry up completely on the alluvial fan. Groundwater from at least two distinct aquifers recharges the creek between these sections. McDougall Creek (and a second groundwater source) recharged the deltaic aquifer (Aquifer ID 233) mapped below the alluvial fan. McDougall Creek appeared to be perched above the aquifer in some seasons.

Penticton Creek - Historically, Penticton Creek was a braided stream that flowed across a large alluvial fan. Severe flooding in the 1940s resulted in the channelization of the creek for flood protection. The creation of a single concrete lined channel has resulted in a loss of stream width and length, fish spawning habitat, and the natural mobility of the stream (Mould Engineering 2017). Restoration of Penticton Creek was approved by Penticton City Council in 2018 to help improve spawning habitat for native fish species and remove deteriorated infrastructure. While this project is still ongoing, approximately 1,200 tonnes of concrete lining have been removed and replaced with rock and gravel to mimic natural pools and riffles (City of Penticton 2023).

Upper Vernon Creek – The upper sections of Vernon Creek (above Winfield) flow across an alluvial fan. To prevent water losses to groundwater and to provide flood protection, the creek was channelized into a concrete flume in the 1960s in the vicinity of the Hiram Walker Whiskey Distillery. Severe flooding in 2017 caused extensive damage to the flume, including sedimentation and burial to a depth of at least 1 m consisting of cobbles and gravels. The concrete channel was damaged in places, and the coarse, underlying fan sediments were eroded. Avulsion occurred during the event and the creek began to follow the original abandoned channel. Sediment transport and deposition were altered by development along the flood flow path. Flow blockages in the channel resulted in multiple shallow channels with low flows blocking fish passage to and from Ellison Lake after the flood. The underlying fan aquifer was recharged for the first time in 45 years leading to groundwater level rises of approximately 5 m above average post-diversion freshet levels and artesian flow in the distal portion of the fan 6-8 weeks after the flood event (Newbury, 2017). Damage to the Holiday Park Resort ensued as the development had occurred without consideration of the potential for this type of catastrophic recharge and return of groundwater flows to pre-channelization conditions. Restoration of the flume and an upgrade to modern standards began in 2018. The concrete flume was replaced with naturalized rock cascades and pool-riffle channels placed on top of a waterproof liner, which prevents infiltration into the stream bed.

Middle Vernon Creek – This reach of Vernon Creek flows out of Ellison (Duck) Lake and travels north through Winfield toward Wood Lake. It is located at the valley bottom and flows across alluvial fan sediments. Middle Vernon Creek is an important kokanee spawning habitat, but chronic low flows in late summer and fall since about 1995 have caused fisheries management issues as have periodic floods. A temporary sandbag structure was used to increase storage in Ellison Lake and enhance September flows. A collaborative project was initiated in 2012 between the provincial government, federal government, and the ONA to determine alternative ways to maximize water use between fish, agricultural, and domestic uses (Epp and Neumann 2017). A Decision Support System model was created as part of the project to simulate multi-year scenarios to predict how flows and lake levels change in response to management. Model simulations suggested that the sandbags are likely detrimental to red and blue listed plants around the lake and that increased flow releases from Swalwell Lake (a managed reservoir at mid elevation) could ensure appropriate flow needs for kokanee during spawning. However, variability in groundwater seepage rates, beaver activity upstream, and dry conditions continue to limit fall flows. Revised Operating Rules were recommended for 2017 and beyond and incorporated additional drawdown of Swalwell Lake levels to ensure that Middle Vernon Creek flow targets for kokanee spawning could be achieved (Epp and Neumann 2017).

Mission Creek – Mission Creek is the largest tributary flowing into Okanagan Lake, and it is important for supplying drinking and irrigation water and for the social, cultural and recreational values it provides (Neumann 2018; Matthews 2022). The lower sections of Mission Creek flow across a large delta fan, and these lower reaches provide critical fish habitat for spawning and rearing. However, the system is stressed, especially during drought conditions. A groundwater-surface water study was initiated by the OBWB along the lower 25 km section of Mission Creek from 2016 to 2018 (Neumann 2018), which built upon similar work conducted by Lowen and Letvak (1981). A combination of piezometers and streamflow gauging was used to compare vertical hydraulic head and between station streamflow, respectively, to identify upwelling (groundwater additions to the stream) and downwelling (loss of streamflow to groundwater) conditions. Piezometer results showed strong downwelling conditions along most of the reaches other than at KLO Road, where both upwelling and downwelling has been observed. Water balance results were consistent with piezometer results, showing gaining conditions where Mission Creek flows through narrow incised valleys and losing conditions where the it flows along alluvial fan deposits (below KLO Road) (Neumann 2018). Conservation and riparian restoration in lower Mission Creek began as a collaborative effort between federal, provincial, First Nation, and local governments in 2003 (Mission Creek Restoration Initiative). Work has included the expansion of the floodplain and the installation of riffles to increase channel stability and fish habitat. Efforts to restore Mission Creek for fish, wildlife and other values are outlined in the Lower Mission Creek Habitat and Restoration Plan (Matthews 2022).

MANAGEMENT CHALLENGES and KNOWLEDGE GAPS

Alluvial fans are common features on the Okanagan landscape, and the vast majority of alluvial fans were formed in the period after deglaciation. Rapid development on alluvial fans over the past 150 years has proven to be problematic in many ways, both for the past and future evolution of the fans (and associated hydrologic, geomorphologic, and ecologic processes) and for the risks posed to human life and infrastructure.

Streams that flow across alluvial fan surfaces are characteristically unstable and prone to braiding and frequent overbank events and channel avulsions. These are natural processes that are central in the build-up and evolution of alluvial fans. However, humans are uncomfortable with such persistently shifting landscapes, and a common engineering strategy is to channelize the stream, often by straightening and hardening the banks (with concrete or rip-rap) thereby constraining the stream to a single, immovable channel. This has occurred on the majority of alluvial fans in the Okanagan Basin. One consequence of channelization and accompanying modifications to the natural water- and sediment-transport processes on fans is that the channel is artificially narrowed, especially at short-span bridges and culverts, to reduce engineering and constructions costs. These locations become bottlenecks during flood events, with significant risk of destruction to the bridge or culvert and major disruption to traffic patterns and closure of emergency routes. The lesson to be heeded is that the intensity of fan surface modification by human activities usually takes the system farther away from its natural state, thereby increasing the risks associated with catastrophic floods and debris flows.

And yet, alluvial fans continue to be desirable locations for development because of ease of excavation in the unconsolidated sediments, relatively flat terrain for construction, well-drained sediments, and sufficient grade to provide vistas to valley bottoms. The sediments in alluvial fans provide a ready source of aggregate (sand and gravel) for construction purposes, and the trees that grow on alluvial fans are easily logged. All these activities lead to modification of the alluvial fan surface, but more importantly to the processes that occur on fans to move water and sediment from the apex to the toe of the fan.

Despite years of study, it remains extraordinarily difficult to predict what the specific ramifications of a particular development project might be. In part, this is due to the complex stratigraphy of alluvial fans and the general lack of information on subsurface stratigraphy and aquifer inter-connectivity. Groundwater wells are often poorly logged, and their spacing is not ideal for stratigraphic reconstruction or modeling. Thus, it becomes virtually impossible to know with any degree of specificity what the impact of road-building or logging might be on: (a) the streamflow hydrograph; (b) surface-groundwater exchanges; (c) aquifer recharge; (d) channel avulsions; and (e) sediment delivery through the system. These uncertainties have additional implications for management of water supply (e.g., streamflow volumes, aquifer dewatering, evapotranspiration) and for ensuring that environmental flow needs are satisfied. In short, we have a broad understanding that there will be impacts, and we know the general nature of those impacts, but we aren't able to model and predict what will happen with any precision or certainty.

Another major challenge is the non-stationarity in hydro-meteorological conditions accompanying climate change. Increasingly, there seems to be either too little water or too much water in the Okanagan Basin depending on the season. Drought conditions will be of key concern for alluvial fans because the volume of water delivered to fan surfaces will decrease, thereby reducing groundwater recharge and increasing the likelihood of there being insufficient water to maintain adequate flows in streams. Much of the sediment delivered to the fan surface will be stored near the apex instead of being transported slowly to the distal areas of the fan. Over time, the increasing sediment volume in the channels will pose a significant hazard in terms of potential debris flows, especially if there are reservoirs upstream prone to dam failure. Depleted stream discharge will affect how water licences are managed in the future, and there are major ramifications for fish habitat. Warmer climatic conditions also imply warmer water in streams, which may lead to fish kills and influence the migratory and spawning behaviour of anadromous species. The problem can be exacerbated when logging removes the vegetative overstory and exposes creeks to direct sunlight or when urban development replaces natural vegetation with concrete and asphalt. In addition, the predicted shift from a snowmelt-dominated system to a rainfall-dominant system and shifting timing of precipitation throughout the year has as-yet incompletely understood effects on water availability and aquatic ecosystems in the valley.

The subsurface stratigraphy of alluvial fans is exceedingly complex comprising a variety of discontinuous strata and lenses with a wide range of grain sizes. This leads to great variation in permeability, which means that fan aquifers are vulnerable to contamination from human activities. Aquifers with highly connected facies and fast groundwater velocities are more vulnerable to contamination, especially by human activities in the recharge zone (Stimson et al. 2001). Sources of contamination include agricultural pesticides and herbicides, industrial fluids (e.g., oils, fuels), human waste products in landfills, urban runoff, toxic spills, and fire retardants (used to fight wildfires). These contaminants can accumulate in low permeability deposits, remaining there for decades to centuries (Bowman 2019).

Developing a general model of fan development and therefore the distribution of hydraulic properties like conductivity is very challenging. Fans with different stratigraphic histories and morphologies will have different recharge characteristics (volumes and dominant processes) (Houston 2002) and understanding the complex stratigraphy is important for understanding variability in hydraulic conductivity. Aquitards act as partial barriers to infiltration potentially redirecting subsurface flow laterally (Bowman 2019). Aquitard deposits are often discontinuous, disconnecting groundwater flowpaths in one area but allowing reconnection where they thin or pinch out (Bowman 2019). This results in spatially variable groundwater velocities and high variability in water residence times across the fan deposits (vertically and laterally) (Bowman 2019). This poses a major challenge for water managers because releases of water from upstream dams for purposes of water supply or to meet environmental flow needs may be lost if there are extensive losing reaches. Farther downstream there may be 'excess' water because of springs and wetlands through gaining reaches.

RECOMMENDATIONS- THE WAY FORWARD

The foregoing summary of what is known about alluvial fans and the associated management challenges, leads to a series of recommendations that may improve the manner in which humans interact with landscapes and waterscapes dominated by alluvial fans. In no order of priority, these recommendations include:

- Foster increased awareness about alluvial fans in the Okanagan across all relevant sectors (i.e., forestry, transportation, urban development, agriculture, fisheries) focusing especially on (a) what they are; (b) how to identify them; (c) where they are commonly found; (d) their importance to water supply and fisheries management; and (e) the risks associated with development and resource use on alluvial fans.
- Collate existing reports that are associated with alluvial fans, particularly those associated with flooding, such as reports for Upper BX Creek in Vernon and for the Central Okanagan Regional

District. Both reports provide hazard and risk assessment methodologies – a common hazard/risk matrix should be developed/accepted for the Okanagan. The Upper BX Creek report provides examples of structural and non-structural mitigation measures (Northwest Hydraulics 2020) – these can be expanded on for the Okanagan valley.

- Encourage the use of advanced analytical techniques to better understand how water moves through alluvial fan systems. For example, there is great potential to use various kinds of tracers (e.g., isotopes) to differentiate between water sources (i.e., "old" vs "new" water) as well as to assess dominant flow pathways within fan stratigraphy. Critical elements include the nature of surface-groundwater exchange processes (volumes, locations, timing) and aquifer storage/transmissivity. The data collected from field investigations can then be used to calibrate and refine groundwater flow models through fan systems, either in general for better scientific understanding or for specific fans where there are management challenges.
- Place our understanding and management of alluvial fan hydrology in a valley-wide context with focus on anticipated effects of climate change (e.g., more extreme rainfall events influencing sediment transport events and debris flows; increased frequency of rain-on-snow events altering the timing of freshet with subsequent implications for ecosystem resilience; longer summer drought periods with impacts on streamflow diversions and groundwater use for irrigaion). Given that much streamflow on fans derives from higher elevations, promote increased spatial distribution of mid-high elevation climate monitoring. Without these data, water management on fans will always be reactive.
- Devise a ranking scheme for known alluvial fans in the Okanagan Basin to prioritize future studies based on: (a) size (area, volume); (b) development pressure; (c) value of infrastructure; (d) habitat value (aqueous, riparian); (e) water demand (licenced volumes allocated, number of wells, fluctuations in groundwater levels); (f) extractive activities such as forestry and mining; and (g) hazard and risk metrics.
- Develop an inventory of Okanagan alluvial fans, prioritized according to the ranking scheme above, that maps their locations and provides relevant details. To this end, the recent LiDAR data base could be exploited to identify new fans and accurately map fans that are known to various stakeholders. This information can then be incorporated into urban planning processes and development permitting, as well as providing critical information to water licencing.
- Explore opportunities to enhance water storage in fan aquifers using knowledge derived from studies of surface-groundwater exchange and aquifer recharge
- Encourage senior levels of government to provide funding to support outreach/educational activities and scientific studies on alluvial fans.

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APPENDIX 1 – Estimated Water Losses and Gains Across Alluvial Fans in the Okanagan Basin (from Summit, 2009, Table 3.5).

Node	Stream	Estimated length of stream flowing over alluvial fan (km)[1]	Assumption for potential net streamflow loss/gain across alluvial fan	Assumed net streamflow loss to (-) or gain from (+) alluvial aquifer as a stream flows across its alluvial fan (m^3/s)[2]
1, 2, 12	Vernon Creek	7.5	No net loss	0
3	Deep Creek	29.6	No net loss (i.e., losses along upper fan are offset by gains along lower fan)	0
5	Irish Creek	1.1	Streamflow is lost to groundwater at a rate of 0.014 m^3/s per km of channel on alluvial fan	-0.02
8	Equesis Creek	7.8	No net loss (i.e., losses along upper fan are offset by gains along lower fan)	0
10	Naswhito Creek	1.9	Streamflow is lost to groundwater at a rate of 0.014 m^3/s per km of channel on alluvial fan	-0.03
14	Whiteman Creek	1.6	No net loss (i.e., losses along upper fan are offset by gains along lower fan)	0
16	Shorts Creek	0.6	Streamflow is lost to groundwater at a rate of 0.014 m^3/s per km of channel on alluvial fan	-0.01
18	Lambly Creek	0.9[3]	Streamflow is lost to groundwater at a rate of 0.014 m^3/s per km of channel on alluvial fan	-0.07
20	Mill (Kelowna) Creek	17.6	No net loss (i.e., losses along upper fan are offset by gains along lower fan)	0
22	Mission Creek	7.5	No net loss (i.e., losses along upper fan are offset by gains along lower fan)	0
24	Bellevue Creek	1.0	Streamflow is lost to groundwater at a rate of 0.014 m^3/s per km of channel on alluvial fan	-0.01
26	McDougall Creek	1.2	Streamflow is lost to groundwater at a rate of 0.014 m^3/s per km of channel on alluvial fan	-0.02
28	Powers Creek	7.4	No net loss (i.e., losses along upper fan are offset by gains along lower fan)	0
30	Trepanier Creek	7.5[3]	Streamflow losses according to Obedkoff (1990)	-0.16
32	Peachland Creek	0.0[3]	Streamflow losses according to Obedkoff (1990)	-0.03
34	Chute Creek	0.0	Streamflow is lost to groundwater at a rate of 0.014 m^3/s per km of channel on alluvial fan	0
36	Eneas Creek	2.5	Streamflow is lost to groundwater at a rate of 0.014 m^3/s per km of channel on alluvial fan	-0.03
38	Robinson Creek	1.0	Streamflow is lost to groundwater at a rate of 0.014 m^3/s per km of channel on alluvial fan	-0.01
40	Naramata Creek	1.0	Streamflow is lost to groundwater at a rate of 0.014 m^3/s per km of channel on alluvial fan	-0.01
42	Trout Creek	2.5	Streamflow losses to groundwater assumed similar to the rate estimated by Trout Creek Water Use Plan Consultative Comm. (2005) for losses upstream of Summerland intake	-0.04
44	Turnbull Creek	1.0	Streamflow is lost to groundwater at a rate of 0.014 m^3/s per km of channel on alluvial fan	-0.01
46	Penticton Creek	2.5	Streamflow is lost to groundwater at a rate of 0.014 m^3/s per km of channel on alluvial fan	-0.03
51	Shingle Creek	2.5	Streamflow is lost to groundwater at a rate of 0.014 m^3/s per km of channel on alluvial fan	-0.03
52	Ellis Creek	2.5	Streamflow is lost to groundwater at a rate of 0.014 m^3/s per km of channel on alluvial fan	-0.03
55	Marron River	0.77	Streamflow is lost to groundwater at a rate of 0.014 m^3/s per km of channel on alluvial fan	-0.01
60	Shuttleworth Creek	2.5	Streamflow is lost to groundwater at a rate of 0.014 m^3/s per km of channel on alluvial fan	-0.03
66	Vaseux Creek	1.5	Streamflow is lost to groundwater at a rate of 0.014 m^3/s per km of channel on alluvial fan	-0.02
69	Park Rill	2.5	Streamflow is lost to groundwater at a rate of 0.014 m^3/s per km of channel on alluvial fan	-0.03
71	Wolfcub Creek	1.1	Streamflow is lost to groundwater at a rate of 0.014 m^3/s per km of channel on alluvial fan	-0.02
73	Testalinden Creek	1.0	Streamflow is lost to groundwater at a rate of 0.014 m^3/s per km of channel on alluvial fan	-0.01
78	Inkaneep Creek	2.5	Streamflow is lost to groundwater at a rate of 0.014 m^3/s per km of channel on alluvial fan	-0.03

Notes:

1. The lengths of stream flowing over the alluvial fan were estimated using GIS and expert judgement. Only losses to the lowermost alluvial aquifer in each sub-basin were considered. Streamflow lost to the other aquifers upstream in the Basin are likely to be followed by gains downstream where the aquifer terminates (e.g., bedrock canyon).

2. The potential losses presented are first approximation based on the very limited data available. Actual losses are likely to vary spatially and temporally (seasonally and annually) in response to streamflow and the relative elevations of the groundwater table and streambed and banks. Local sub-surface conditions also will influence actual streamflow losses or gains that occur. Further investigation is required to gain confidence in the estimate.
3. The lengths of stream over which losses were estimated by Obedkoff area as follows: Lambly Creek: 5.6 km, Trepanier Creek: 7.5; Peachland Creek: 3.4 km.