APPENDIX D

Alluvial Fan Flooding

Alluvial fan flooding is a hazard to communities in the mountainous regions of the western United States. Alluvial fan flooding is characterized by a sudden torrent of water capable of carrying rocks, mud, and debris that debouches from the steep valleys and canyons and spreads over the fan surface. The type of detailed flood damage mitigation information available for other flood-prone areas is limited for alluvial fan situations. Fan flood flows are characterized by surging, erosion, scour, channel avulsion, mud and debris flows, and sheet flows on the lower portions of the fan surface. Each fan flood event as well as each fan can exhibit different flood characteristics.

NOTE

For more information regarding alluvial fans, see:

FEMA's webpage: http://www.fema.gov/plan/prevent/floodplain/nfipkeywords/alluvial_fan_flooding.shtm

Living with the River (Washington State Department of Ecology, 2007).

FEMA 165, *Alluvial Fans: Hazards and Management* (FEMA, 1989). FEMA 165 provides an overview of alluvial fans and related management issues, and briefly discusses retrofitting of individual residential structures

Development over the last several decades has proceeded with little cognizance of the potential for flood hazards. Many fan communities are now preparing flood management and mitigation plans, but existing structures may have to rely on floodproofing measures to reduce flood damage. Fan-wide master plans for zoning and fan-wide mitigation measures are crucial for successful protection of the community as a whole. Where master plans or mitigation schemes are inadequate or nonexistent, floodproofing and retrofitting of residences may provide the only reasonable methods for flood loss reduction.

This appendix includes a description of alluvial fan flooding and associated hazards; an overview of the regulatory framework and building code issues unique to fan areas; and design considerations for retrofitting in alluvial fan flooding areas.

D.1 Alluvial Fan Flooding Basics

Most alluvial fan floods are caused by high-intensity, short-duration summer thunderstorms. Longer duration rainstorms and spring snowpack melt, volcanically-induced flooding, and failure of water storage facilities can also cause alluvial fan floods. Alluvial fan floods can occur without warning. Both the hydraulic and hydrologic flood characteristics of alluvial fans are highly variable from fan to fan, which may be in different stages of episodic growth. A geologist, geomorphologist, hydrologist, or hydraulic engineer experienced in alluvial fan technology should be consulted to identify alluvial fan characteristics and the possible response to flooding.

There are three zones that may be identified on the surface of an alluvial fan (Figure D-1). Each zone has unique hydraulic and sediment-transport processes during a flooding event, as well as a unique hazard level. The exact location of each zone on a given fan is dependent on flooding characteristics, but usually can be identified on the fan surface after a recent flood event. These zones are:

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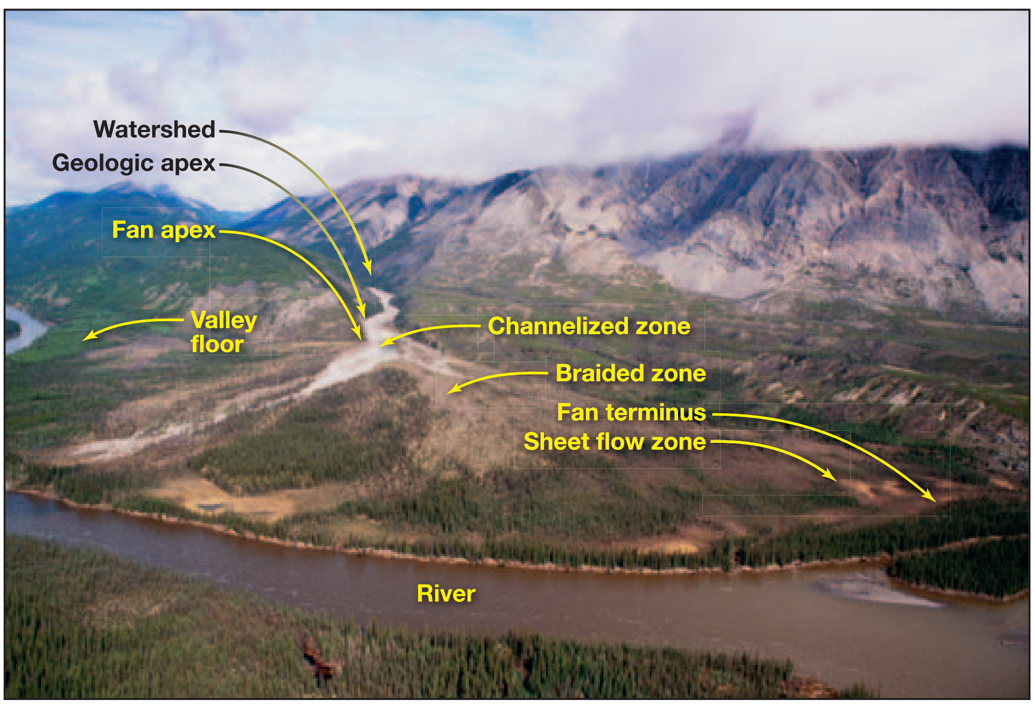
In mountainous regions in the west, floodwater may spread out in a fan shape as it flows from the mouth of a watershed to the valley below. The floodwater erodes the steep slopes of the watershed and deposits sediment in a cone or fan shape over the flatter land. Over time, this process creates a land form known as an alluvial fan.

Channelized Zone: Generally located at and below (downstream of) the fan apex. Flow within this zone is confined to well-defined channels, although channels may split or abruptly change direction. This zone is associated with hazardous flooding conditions related to high flow velocities, boulder and debris impact, and channel scour. If channels are deeply incised, this zone may extend further down the fan.

Braided Zone: Downstream of the channelized zone, characterized by flow with an unstable pattern of numerous interlacing shallow channels. Flood hazards in this zone are related to flood inundation and sediment deposition, rather than high flow velocity or debris impact. Large boulder transport is generally absent in this zone.

Figure D-1.
Alluvial fan flooding zones and other geologic features



Sheet Flow Zone: Downstream of the braided zone characterized by flow depths less than ½ foot (flow depths normally decrease in the downfan direction). Smaller channels may aggrade while other areas are subject to erosion or scour. Flow may continue to spread laterally until sheet flow is predominant. Floods are usually limited to inundation by low velocity floodwater.

Streets and buildings can change the composition of a fan zone by redistributing floodwater over the fan surface. The altered flood response can impact areas on the fan that may have been considered outside the originally delineated flood hazard zone. As a fan is developed, delineation of flood hazards may change.

D.2 Alluvial Fan Flooding Hazards

While alluvial fans present flood hazards found in riverine flooding such as inundation and differential hydrostatic loading, they are often compounded by high velocities, hyperconcentrated sediment flows, severe erosion, and extensive sediment deposition. Structures on alluvial fans may be susceptible to damage caused by high velocity water; lateral loading that forces structures off foundations or induces wall collapse; water inundation; scour and undermining of buildings; impact of mud, debris, and boulders; sediment burial; and landscape erosion.

Alluvial fan processes and the resultant fan morphology are dependent upon hydrologic conditions of the upstream watershed. Factors contributing to devastating fan flooding include; high intensity rainfall events on sparsely vegetated steep slopes; steep watershed slopes with highly erosive soils or unstable geologic formations; sediment buildup and storage in watershed channels; saturated soil conditions from antecedent rain and snowmelt; recent forest fires, logging, or other soil-destabilizing activities in the watershed; intensity and configuration of development of the fan and failure of flood mitigation measures.

Fan flooding can occur through the continuum of sediment transport processes from clear water flows to hyperconcentrated sediment flows such as mud floods and debris flows.

A **water flood** is the inundation of the fan surface from overbank discharge or rainfall/snowpack runoff. Fan water floods are common in the southwest desert. Water flooding can cause damage by inundating the lowest floor, scouring and undermining structures, displacing buildings from foundations, physically tearing apart structures, or depositing sediment in basements and yards. Sediment loads are less than 20 percent of the total flow and do not significantly affect fluid flow properties.

When the concentration of sediment in the flow reaches 20 to 40 percent by volume, the flow is considered to be “hyperconcentrated” and can be defined as **mud flow**. Mud flows can be destructive to buildings because they are usually associated with high velocity flows. In addition to the property damage for a water flood, mud flows can cause severe property damage related to sediment deposition and result in loss of life. Cleanup costs can be significantly higher for a mud flood than a water flood. Damage results from inundation by mud, impact of mud frontal waves, and high lateral loading, which can result in structure collapse. Mud flows can raft large boulders and debris on their flow surfaces, causing substantial impact damage.

NOTE

The July 24, 1977, mud flows in Glenwood Springs, Colorado, resulted in approximately $500,000 (1977 dollars) in damage, most of which involved mud removal.

Debris flows are hyperconcentrated flows with a sediment concentration that may be greater than 55 percent by volume. They consist primarily of rolling and tumbling boulders and debris and only a limited amount of fluid for lubrication. Fifty percent or more of the particles in a debris flow are generally larger than sand. The alluvial fans of the Pacific Northwest, Rocky Mountains, and the West Coast ranges can experience severe mud and debris flows whose surges can engulf entire buildings, resulting in structural damage, movement, or complete collapse.

WARNING

Debris flows are less likely to occur than water or mud floods, but can cause more damage due to the impact of high velocity boulders or debris waves, which crash through building walls or knock structures off foundations.

Channel avulsion is the episodic, and often erratic, shift of a channel's path. Channel avulsion may be initiated by sediment deposition that can fill or block the channel, forcing the flow to create a new path, or by bank erosion, through which the flow will be diverted. The new flow path will often follow a steeper course. Structures located in the path of a newly forming channel are often undermined and destroyed.

Frontal waves, surging, and hydrostatic pressure are significant flood hazards associated with alluvial fan flooding. Mud flows and debris flows can have frontal waves up to 15 feet high. Surging increases the flood hazard by subjecting structures to significantly higher flow depths and velocities. Surges have been observed at 8 feet high, and more than double the flow depth. Once the mud or debris flow has ceased, the resulting sediment deposition against a building can exert large lateral pressures that may be nonuniform across the face of the wall. In addition to the impact and differential hydrodynamic loading related to mud flows, the weight of the deposited mud can cause structural damage to buildings designed to withstand predicted hydrostatic and hydrodynamic loads. Often large boulders, trees, or other debris will come to rest against the upfan side of a building, contributing to the nonuniform lateral load on a wall.

WARNING

The depth of flooding shown on FIRMs for alluvial fans should be considered an estimate for the entire fan area, not an absolute value. Alluvial fan flood depths may vary from the given flood depth by several feet, depending upon local conditions. Site-specific analysis should be undertaken to accurately determine flood depth for a retrofitting project.

D.3 Regulatory Framework and Building Code Issues for Alluvial Fans

Within the regulatory context of the National Flood Insurance Program (NFIP) and building codes, alluvial fan flooding poses special problems for individuals and agencies trying to interpret guidelines prepared specifically for riverine flooding conditions.

Although FEMA recognizes alluvial fan flooding hazards, guidelines do not specifically address mud and debris flow hazards or sheet flow inundation on urbanized alluvial fans. Unmapped urbanized fans are not subject to FEMA/NFIP insurance or mitigation criteria. In response to increased exposure to fan flooding, some communities have undertaken flood hazard delineation and have instituted local ordinances and regulations for fan development. In most states, there are no guidelines or regulations governing hazard delineation, zoning regulations, or mitigation for new construction.

In communities that have not adopted specific alluvial fan flood hazard regulations and ordinances, it is left to the developers and homeowners to mitigate flood hazards or implement floodproofing. Progressive communities have conducted studies to more effectively determine the extent of flood hazards. Once the potential for the flood hazard is understood, a permitting and review body can draft ordinances and regulations governing development on alluvial fans. Residential retrofitting methods should be compatible with comprehensive alluvial fan flood hazard mitigation and master drainage plans. Integration of the retrofitting method with existing drainage and mitigation measures (such as streets designed as conveyance channels) can reduce flood damage in densely populated neighborhoods. Floodproofing should direct flows into desirable paths such as streets or dedicated flow-through areas, and should not encroach on setback distances. Regulations may require setbacks from existing channels.

Every fan has areas of extreme flood hazards where hazard avoidance is essential. If "no build" zones have been designated, building permits should be denied within these zones (often in the channelized and braided zone). The idea that deflection of floodwater can be caused by structures should be considered. Local ordinances may specify that the proposed retrofitting must be able to pass the flood through the property or development without increased damage to other structures. NFIP regulations concerning conveyance around a new structure in Zone AO may also be applied to retrofitting situations.

NOTE

A well-integrated approach to floodproofing and fan flood mitigation can reduce flood losses and possibly lower flood insurance costs where the measures are approved by FEMA.

In addition to the minimum requirements of the NFIP, the International Residential Code (IRC) addresses building requirements for structures located in riverine flood hazard areas designated by approved flood insurance maps or the local floodplain management ordinance. Under the IRC, building design is required to withstand the forces associated with the base flood level of the 1-percent-annual-chance flood event. The IRC requires the use of well-established engineering principles in the design of structural members to resist flotation, stress increases, overturning, collapse, or permanent lateral movement due to flood-induced loads (hydrostatic, hydrodynamic, and impact loads).

Finally, structural flood mitigation and floodproofing measures should also be integrated into the community master emergency plan to avoid impeding emergency services during a flood event. The diversion of flow by a floodwall into a designated emergency route may eliminate access to areas of the fan by emergency equipment.

D.4 Design Considerations for Retrofitting in Alluvial Fan Flooding Areas

Residential retrofitting measures may include relocation, elevation, floodwalls and levees, building reinforcement, dry floodproofing, site grading, and landscaping. Retrofitting measures can be permanent, contingent, or emergency. In general, fan flooding occurs with very little warning, limiting the effectiveness of contingency or emergency measures that require human intervention.

WARNING

Residential retrofitting measures should be compatible with the master plan components. Retrofitting can negatively impact the downfan flood hazards when not considered in the context of a master drainage plan.

D.4.1 Relocation

When considering relocation as a retrofit option, master drainage plans, hazard zone delineation, building codes, public purchase of land, open space dedication, and land trades are all considerations. Although relocation is a significant undertaking, it may be economically feasible considering the potential threat to lives and property on the upper reaches of the fan.

D.4.2 Elevation

When considering elevation as a mitigation retrofit, consider that the NFIP and IRC require that new or substantially improved/damaged structures must be elevated at least to the flow depth indicated on the Flood Insurance Rate Map (FIRM), or at least 2 feet if no depth is given. Local regulations may also require additional freeboard. In areas of potential mud, debris, and high-velocity flows, additional freeboard should be considered.

Elevation on posts or piles permits floodwater to pass underneath the structure, causing little obstruction to flow. A properly designed pile will carry all inherent structural loads and lateral loads (hydrodynamic and impact) expected during the design flood. An additional important design consideration for piles is potential scour. Spacing of posts and piles should be relatively wide to minimize flow constriction or the collection of debris found in the watershed or on the fan. The failure of supporting members could potentially cause more damage than inundation of a non-elevated structure. In contrast, elevation on fill may impose a significant obstruction to the flood path; therefore, constriction and diversion of flow onto adjacent properties is a concern. Application and compaction of fill should follow standard engineering practices. The toe of the fill slope must be protected from scour; this slope protection should be extended at least 2 feet below grade. The fill slope above grade should be protected by rock rip-rap or vegetation to at least the base flood level.

D.4.3 Floodwalls and Levees

Floodwalls and levees may be considered on the upfan portion of a building to protect it from the forces of moving water and inundation. The height of floodwalls should be based on a specified design maximum flow depth plus freeboard. The estimated freeboard should include velocity head, wave height, potential flow runup, potential for sediment deposition against the wall, and surging. Design height for floodwalls and levees should be limited to 3 to 4 feet. Floodwalls should be constructed below grade to provide protection from scour. Stability design should take into account material removed by scour. Frequently utilized on riverine floodplains, levees may require some modification when applied on alluvial fans. On alluvial fans, levees can divert flow around a subdivision or residence, or they may provide protection along a natural or engineered channel through a developed area. Levees should be designed to protect against scour and levee slope erosion.

On steep alluvial fan slopes, the complete enclosure of a structure by a floodwall and levee is not usually necessary, and the downfan side of the property does not require a floodwall. Closures should not be included in the protective structure because failure of the closure may cause complete failure of the floodwall or levee. In some instances, floodwalls have been used primarily for protection against mud and debris flows, without restricting seepage but ensuring structural stability.

The U.S. Army Corps of Engineers (draft report, undated) recommends avoiding this retrofitting alternative for mud and debris flows where the overtopping or failure of levees and floodwalls can cause catastrophic damage in excess of the damage that would have occurred in an area devoid of protection. Mud and debris flow deposition on the upfan side of the wall or levee may increase the potential for overtopping or runup. The use of floodwalls and levees is most appropriate in fan flood hazard zones characterized by low and moderate velocity flows or mud flows in low density development.

D.4.4 Building Reinforcement

Structures located in areas subject to hydrodynamic and impact forces from water, mud, and debris flows can be protected against damage and collapse through structural reinforcement of upfan walls. Reinforcement may include the addition of structural supporting members or an exterior facade, or the removal and replacement of existing walls. In conjunction with the reinforcement of upfan walls, removal of openings in the upfan wall should be investigated. If these openings are removed, they may need to be replaced with openings on other walls. Weak points in the bearing wall, such as windows, doors, and utility connections, may leak or fail under flooding conditions and should be reinforced and floodproofed or eliminated. Reinforcement of upfan walls should be designed for impact pressures and hydrodynamic loading related to mud and debris flows.

D.4.5 Dry Floodproofing

Dry floodproofing is appropriate for shallow flooding zones where the base flood elevation is not determined. This technique can be used for brick veneer and masonry structures where floor slabs are rigidly connected to walls.

WARNING

Dry floodproofing is not allowed by FEMA for new or substantially improved or damaged residential structures located in a Special Flood Hazard Area.

External dry floodproofing consists of an impervious layered sheet material such as tar or asphalt bitumen applied to the exterior of the building. Excavation around the foundation may be required to externally floodproof building material below the ground surface subject to soil saturation during the flooding event. Membrane materials should be designed to resist all expected flooding conditions including scour, abrasion, impact, and hydrostatic and hydrodynamic pressures. On alluvial fans subject to mud and debris flows, the external membrane cannot be exposed to the flow. External membranes may not be required on the downfan side of a building.

D.4.6 Other Techniques

Two other techniques, site grading and landscaping, can also be used. Site grading can be effective as a flood protection method for existing homes if the predicted flooding is relatively shallow and the runoff from the property can be handled by existing stormwater facilities. Site grading or standard landscaping designs should be considered for the sheet flow zone of alluvial fans (< 1 foot in depth). Flood flows may be dispersed with landscaping that splits the flow with wedged flow barriers or through vegetated areas. Landscaped low mounds may be oriented to divert flows to an on-site drainage path or off-site flow conveyance area. Landscaping may not be compatible with flows having high sediment loads.

D.4.7 Relevant Equations for Computation

Equations for the computation of sediment-water mixtures, hydrodynamic forces, freeboard, and factor of safety recommendations are provided below.

Bulking Factor: The design flood conditions must be evaluated considering the increased flood discharge related to sediment bulking. For semi-arid alluvial fans, typical bulking factors range from 1.1 to 1.2 for sediment concentrations of 0.10 to 0.15 by volume. Bulking factors for mud flows can be as high as 2.0 (C_v = 0.50). The bulking factor, BF, is given by Equation D-1.

NOTE

Concentration of Sediment (C_v) values are estimated by engineers experienced with this type of analysis and typically range from 0 to 50 percent (decimal equivalent).

EQUATION D-1: BULKING FACTOR

$$BF = \frac{1.0}{1.0 - C_v} \qquad \text{(Eq. D-1)}$$

where:

BF = dimensionless factor applied to riverine discharge values (Q) to account for sediment bulking

C_v = concentration of sediment of the fluid mixture by percent (decimal equivalent) of volume

WARNING

In hyperconcentrated sediment flows, where the sediment concentrations range from 20 to 45 percent sediment by volume, the hydrostatic pressures can be 30 to 75 percent greater than from clear water.

Hydrostatic and Hydrodynamic Loads: Hydrostatic loading is the force of the weight of standing water acting in a perpendicular manner on a submerged surface. Sediment suspended in floodwater will increase the specific weight of the fluid as a function of sediment concentration by volume (C_v). Water with a high sediment concentration will impose greater hydrostatic pressures than clear water. Likewise, hydrodynamic loading is related to the density of the fluid, which will increase with sediment loading. The greater mass the fluid has, the more momentum it will transfer when it impinges on an obstacle. To include the effects of sediment loading in hydrostatic and hydrodynamic calculations, the specific weight of water is replaced with the specific weight of the water-sediment mixture (Equation D-2).

NOTE

In alluvial fan situations, hydrostatic and hydrodynamic forces developed using Equations 4-4 through 4-10 should be recomputed replacing the specific weight of water (γ) with the specific weight of the water-sediment mixture (γ_s).

EQUATION D-2: SPECIFIC WEIGHT OF WATER-SEDIMENT MIXTURE

$$\gamma_s = (1 - C_v)\gamma_w + C_v S_p \gamma_w \qquad \text{(Eq. D-2)}$$

where:

γ_s = specific weight of the water-sediment mixture (lb/ft^3)

C_v = sediment concentration by volume expressed as a percent (decimal equivalent)

γ_w = specific weight of water (62.4 lb/ft^3 for fresh water and 64.0 lb/ft^3 for salt water)

S_p = specific gravity of sediment (dimensionless)

The additional live load attributed to sediment should be considered in all calculations of hydrostatic loading with volumetric concentration of 5 percent or greater. This additional hydrostatic load will be most significant near the fan apex where sediment concentrations are higher and will decrease in the downfan direction. The loading factor related to sediment will be negligible in the sheet flow zone.

Freeboard: Freeboard is the additional design height of walls, levees, and foundations above the base flood level to account for velocity head, waves, splashes, and surges. The conditions of superelevation and flow runup can be severe for mud, debris, and high velocity flows and should be evaluated separately. The U.S. Army Corps of Engineers (draft report, undated) recommends that the amount of freeboard be based on the velocity head plus the increase in depth caused by a 50 percent increase in flow rate, with a minimum value of 2 feet in alluvial fan situations, expressed by the equation shown in Equation D-3:

EQUATION D-3: RECOMMENDED FREEBOARD

$$f = (d_{1.5Qdesign} - d_{Qdesign}) + \frac{V^2}{2g} \qquad \text{(Eq. D-3)}$$

where:

f = recommended freeboard (ft)

V = velocity of flow (ft/sec)

g = acceleration of gravity (32.2 ft/sec^2)

$d_{1.5Qdesign}$ = depth of flooding from a discharge 50 percent greater than the design discharge (ft)

$d_{Qdesign}$ = depth of flooding from the design discharge (ft)

Factors of Safety: A factor of safety greater than 1 is an additional measure of safety to account for unanticipated or unquantifiable factors. In the case of retrofitting on alluvial fans, additional safety should be built into the design, depending on the engineer's perception of the sensitivity of the flow conditions to change. The engineer must also weigh the cost of obsolescence if a retrofitting technique becomes inadequate with continued development. Factors of safety are always a compromise between the desire for added protection and the additional costs associated with retrofitting design and construction. Freeboard and factor of safety recommendations are provided in Table D-1.

Table D-1: Freeboard and Factor of Safety Recommendations

Freeboard and Factor of Safety Recommendations		
Type of Flooding	**Freeboard (ft)**	**Factor of Safety**
Shallow water flooding, <1 ft (FIRM Zones A and B)	1	1.10
Moderate water flooding, < 3 ft	1	1.20
Moderate water flooding, < 3 ft with potential for debris, rocks < 1 ft diameter sediment	1	1.20
Mud floods, debris flooding < 3 ft, minor surging and deposition, < 1 ft boulders	2	1.25
Mud flows, debris flows < 3 ft, surging, mud levees, > 1 ft boulders, minor waves, deposition	2	1.40
Mud and debris flows > 3 ft, surging, waves, boulders > 3 ft, major deposition	3	1.50

SOURCE: COLORADO WATER CONSERVATION BOARD, 1986

D.5 References

Colorado Water Conservation Board. 1986. *Colorado Floodproofing Manual*.

Federal Emergency Management Agency (FEMA). 1989. *Alluvial Fans: Hazards and Management*. FEMA 165. http://www.fema.gov/library/viewRecord.do?fromSearch=fromsearch&id=1633.

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