CHAPTER 12

UNIQUE HYDRAULIC CONDITIONS

SECTION 1
ALLUVIAL FAN HAZARDS

CHAPTER 12
UNIQUE HYDRAULIC CONDITIONS

SECTION 1
ALLUVIAL FAN HAZARDS

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER 12
UNIQUE HYDRAULIC CONDITIONS

SECTION 1
ALLUVIAL FAN HAZARDS

1.1 INTRODUCTION

Presented in this section are requirements of engineering analyses, land management criteria, and mitigation measures for use in areas subject to alluvial fan flooding. Alluvial fans are landforms constructed from deposits of alluvial sediments or debris flow materials. These deposits, alluvium, are an accumulation of loose, unconsolidated to weakly consolidated sediments. They tend to be coarse-grained, especially at their mouths. At their edges, however, they can be relatively fine-grained. Alluvial fans have the shape of a fan, either partly or fully extended. Flow paths may radiate outward to the perimeter of the fan, however, drainages may exhibit a range of patterns such as dendritic, anastomosing, and distributary. Alluvial fans are located at a topographic break where long-term channel migration and sediment accumulation become markedly less confined than upstream of the break.

Alluvial fans, and flooding on alluvial fans, show great diversity because of variations in climate, fan history, rates and styles of tectonism, source area lithology, vegetation, and land use. This diversity dictates any analysis approach to consider site-specific conditions in the design of flood control facilities on alluvial fans.

The Federal Emergency Management Agency (FEMA) has recognized that delineation of a floodplain on an alluvial fan cannot be accurately accomplished by using traditional methods of floodplain analysis (i.e., HEC-RAS). Alluvial fan flooding encompasses both active alluvial fan flooding and inactive alluvial fan flooding. (See Figure CH12-F101). Active alluvial fan flooding is characterized by flow path uncertainty so high that this uncertainty cannot be ignored in realistic assessments of flood risk or in the reliable mitigation of the hazard. Inactive alluvial fan flooding is similar to traditional stream flood hazards along the drainage channel. Flooding on active alluvial fans is the primary concern due to the difficulties in accurately identifying and accounting for the flood flow path in an actual flood event.

Several types of flooding occur on alluvial fans. The most common are flooding along the stable channels, sheetflow, debris flow, and unstable flow path flooding. The broad spectrum of alluvial fan landforms and types of flooding requires a flexible approach that is based on site-specific evaluations of the flood hazards on each individual alluvial fans.

1.2 INVESTIGATION

Identification of an area potentially subject to alluvial fan flooding is initially determined from field observations and topographic information. When it is determined than an area may be subject to alluvial fan flooding, a thorough reconnaissance of the area should be made in order to determine the source of flooding, the apex, the boundaries of the area, the limits of entrenched channels and the locations of barriers to flow (natural or manmade) that render some areas more flood prone than others, and locations of single- and multiple-channel regions.` The reconnaissance should make use of available topographic, geologic, and soil maps, aerial photographs, historic records, and site inspections.

1.3 CHANNEL LOCATION

As stated in the introduction, the degree to which the processes that characterize alluvial fan flooding can vary greatly. During a major flood event on an active fan, flow does not spread evenly over the fan, but is confined to only a portion of the fan surface that carries the water from the apex to the toe of the fan. In the upper region of the fan, flood flows are typically confined to a single channel, which is formed by the flow itself through erosion of the loose material that makes up the fan. Because of the relatively steep slopes in the upper region, flood flows are at critical depth and critical velocity. Below the apex of the fan, the flood follows a random path down the fan surface. Under natural conditions, the flood is no more likely to follow an existing channel than it is to follow a new flow path. In the lower region of the fan, flood flows may split and form multiple channels. Sub-critical flow conditions may exist in the multiple-channel region.

During a flood event, the flow may abandon the path it has been taking and follow a new one. That occurrence, termed an avulsion, can result from floodwater overtopping a channel bank and creating a new channel often because debris blocks the channel.

1.4 ANALYSIS

The approach outlined by FEMA for alluvial fan flooding identification is first to identify whether the area under study is an alluvial fan and second, which portions, if any, are characterized by or subject to active alluvial fan flooding. After these steps, various methods unique to different situations can be employed to analyze and define the extent of alluvial fan flooding. Each of these stages should be addressed and documented.

1. Recognizing and characterizing alluvial fan landforms
2. Defining the nature of the alluvial fan environment and identifying active and inactive areas of the fan
3. Defining and characterizing the extent of flooding, or floodplain, within the defined areas

Stage 1: Recognizing and characterizing alluvial fan landforms

Alluvial fan flooding occurs only on alluvial fans. Therefore, the first stage of the analysis is to determine whether the landform in question is an alluvial fan. An alluvial fan is a sedimentary deposit located at a topographic break such as the base of a mountain front, escarpment, or valley side, that is composed of streamflow and/or debris flow sediments and has the shape of a fan, either fully or partially extended. Alluvial fans are constructed from deposits of alluvial sediments or debris flow materials. Geologic maps and field reconnaissance can be used to determine whether the landform is composed of alluvium.

The topographic apex of an alluvial fan is at the extreme upstream extent of the landform. The hydrographic apex is the highest point on the alluvial fan where there exists physical evidence of channel bifurcation and/or significant flow outside the defined channel, as shown in Figure 1. It is noted, however, that previous flow paths may exist in the inactive area of the fan.

The toe of an alluvial fan can be defined as a stream that intersects the fan and transports deposits away from the fan, a playa lake, an alluvial plain, or a piedmont plain. The lateral boundaries are the edges of deposited and reworked alluvial materials. The lateral boundary of a single alluvial fan typically is a trough, channel, or swale formed at the lateral limits of deposition. The lateral boundary may also be a confining mountainside.

Stage 2: Defining active and inactive areas

Although active alluvial fan flooding has occurred on all parts of an alluvial fan at some time in the geologic past in order to construct the landform itself, this does not mean that all parts are equally susceptible to active alluvial fan flooding now. This stage attempts to delineate areas of the alluvial fan that are active or are inactive in the deposition, erosion, and unstable flow path flooding that builds alluvial fans.

The term active refers to that portion of an alluvial fan where deposition, erosion, and unstable flow paths are possible. If flooding and deposition have occurred on a part of an alluvial fan in the past 100 years, that part of the fan can be considered active. This conclusion can be supported by historic records, photographs, aerial photography, and engineering and geomorphic information. If flooding and deposition have occurred on a part of an alluvial fan in the past 1,000 years, for example, that part of the fan may be subject to future alluvial fan flooding. This conclusion may only be supported by geomorphic information. Because there is no clear analytical technique for making such projections, this stage involves systematically applied judgment and the combination of hydraulic computations and qualitative interpretations of geologic evidence concerning the recent history and probable future flooding. The intent of this stage is to narrow the area of concern regarding active deposition, erosion, and unstable flow paths over a period of time generally exceeding 100 years. The combination of engineering and geomorphic analyses provide an indication of the approximate spatial extent of the possible flooding over a relatively long time period (i.e. several thousand years).

Older alluvial fan surfaces are considered active if any of the following are true:

- The recent active sedimentation zone is migrating into the older surface
- The elevation difference between the recently active sedimentation zone and the older surface is small relative to flood, deposition, and debris depths conceivable in the current regime of climate, hydrology, or land use in the source area
- Upstream of the site, there is an opportunity for avulsions that could lead channels or sheet flows across the older surface

For a given area of the alluvial fan, if the situations described above do not exist, then the area is considered inactive and not subject to the deposition, erosion, and unstable flow path flooding that builds alluvial fans. Inactive areas may be subject to flooding though, most notably within entrenched channels. All inactive areas with stable flow path flooding and all active areas may be considered flood prone.

Stage 3: Defining the 100-year flood within the defined areas

The National Flood Insurance Program (NFIP) uses the 100-year flood, the flood having a 1-percent chance of being exceeded in any given year, to delineate the Special Flood Hazard Area (SFHA). This stage will determine the severity and delineates the extent of the 100-year flood within any flood prone area identified in Stage 2.

The analysis of the flood hazards on alluvial fans requires a flexible approach that is based on site-specific evaluations. Several methods are available to quantify the 100-year flood. Not all are appropriate for all situations.

Risk Based Analysis
The U.S. Army Corps of Engineers has provided a framework that may be used to analyze flood hazards on alluvial fans using the principles of risk-based analysis in *Guidelines for Risk and Uncertainty Analysis in Water Resources Planning* (1992). The degree of uncertainty associated with a prediction of a given scenario is assessed by bringing to bear evidence derived from geomorphologic and other studies.

FAN Program
The FEMA developed FAN computer program provides one method of analyzing the flood hazards on alluvial fans. The program provides for the situation where flows are near normal depth in multiple channels. Program output includes results for this situation in addition to the single channel at critical depths. Refer to *FAN an Alluvial Fan Flooding Computer Program User's Manual and Program Disk (FEMA, 1990)* for more information.

Hydraulic Analytical Methods
Inactive, yet flood prone areas should use riverine hydraulic analytical methods. Where flow paths are stable and flow is reasonably confined, standard hydraulic engineering methods such as backwater computations may be used to define the elevation, velocity, and extent of the 100-year flood. Two-dimensional models are typically used for determining flood hazards when flows contain high amounts of sediment, unconfined flows, splitflows, mud/debris flows, and complex urban flooding. One-dimensional sediment transport models are also useful for the analysis of conditions on alluvial fans.

Geomorphic Data, Post-Flood Hazard Verification, and Historical Information
The geomorphic approach is for active alluvial fans where deposition, erosion, and unstable flow paths are possible. Traditional engineering methods generally are inappropriate for areas with these hydraulic characteristics. In some situations the information collected in Stage 2 (identification of active and inactive areas) may be useful to delineate an approximate floodplain on an alluvial fan. In situations where geomorphic field investigations, coupled with historical documentation, and documentation of hydrologic and hydraulic characteristics of flood events (post-flood hazard verification) is available, an approximate floodplain delineation is possible.

Composite Methods

Site-specific conditions on alluvial fans may lend themselves to the use of multiple or combined methods described above for the determination of flood hazards. For example, in areas that contain manmade conveyance channels or deeply entrenched stable channels, one can combine the results of traditional hydraulic computer programs with methods for analyzing active areas.

1.5 DESIGN REQUIREMENTS

Development on alluvial fans is typically more risky than along riverine flooded areas. There are numerous examples of developments on alluvial fans which were thought to be safe and protected but which have subsequently experience severe flooding conditions and substantial damage. Thus, the decision process which should be followed for development of alluvial fans is:

- Avoidance
- Minimization
- Mitigation

If there are compelling reasons to allow development on an alluvial fan, then the hazard must be minimized and mitigated.

In preparation of development on an alluvial fan, the following items must be addressed.

1. Analysis to quantify the design discharges and the volumes of water, debris, and sediment associated with the 100-year flood at the apex of the fan under current watershed conditions and under potential adverse conditions (e.g., deforestation of the watershed by fire). The potential for debris flow and sediment movement must be assessed on the basis of the characteristics and availability of sediment in the drainage basin above the apex and on the alluvial fan.
2. Analysis which demonstrates that the proposed facilities will accommodate the 100-year peak discharge, consisting of the total volume of water, debris, and sediment previously determined as well as the associated hydrodynamic and hydrostatic forces.
3. Analysis which demonstrates that the proposed facilities have been designed to withstand the potential erosion and scour forces.
4. Analysis or evidence which demonstrates that the proposed facilities will provide protection against flows that migrate or suddenly move to the project site from other portions of the fan.
5. Analysis which assesses the methods by which concentrated floodwater and the associated sediment load will be disposed of and the effect of those methods on adjacent properties.
6. Analysis which demonstrates that flooding from local runoff, or sources other than the fan apex, will be insignificant or will otherwise be accommodated by appropriate flood control or drainage measures.

1.6 ALLUVIAL FAN FLOOD PROTECTION MEASURES

Three general flood hazard management approaches may be taken on alluvial fans. They are based on size and density of the planned development.

1. Whole fan protection
2. Subdivision or localized protection
3. Single lot/structure protection

Whole Fan Protection

Whole fan protection can be achieved by utilizing the following measures:
1. Levees
2. Channels
3. Detention basins
4. Debris basins/fences/deflectors/dams

Whole fan protection includes large scale structural measures appropriate to use on extensively developed fans, and which are most cost effective in high density situations. Structures must be designed to intercept upstream watershed flow and debris at the apex and transport it around or through the entire urbanized fan. Structures must be designed to withstand scour, erosion, sediment deposition, hydrostatic forces, impact and hydrodynamic forces, and high velocity flows.

Continued maintenance is essential for optimum operation and can be relatively costly. These structures are most often funded through federal and state sources, but can also be financed through special regional districts, local governments, or developers.

Subdivision or Localized Protection

Individual subdivision or a localized development can be protected from flood hazards by utilizing the following measures:

1. Drop structures
2. Debris fences
3. Local dikes, channels
4. Site plans to convey flow
5. Street design to convey flow
6. Elevation on armored fill

These are smaller scale measures that can be used throughout moderate density fans to safely trap debris and to route water and sediment around or through individual residential developments.

Single Lot/Structure Protection

A single lot or a structure can be protected from flood hazard by using the following protection measures:

1. Elevate and properly design foundations
2. Floodwalls and berms
3. Reinforcement of uphill walls, windows and doors against debris impact

These measures are most cost effective when implemented at low development densities.

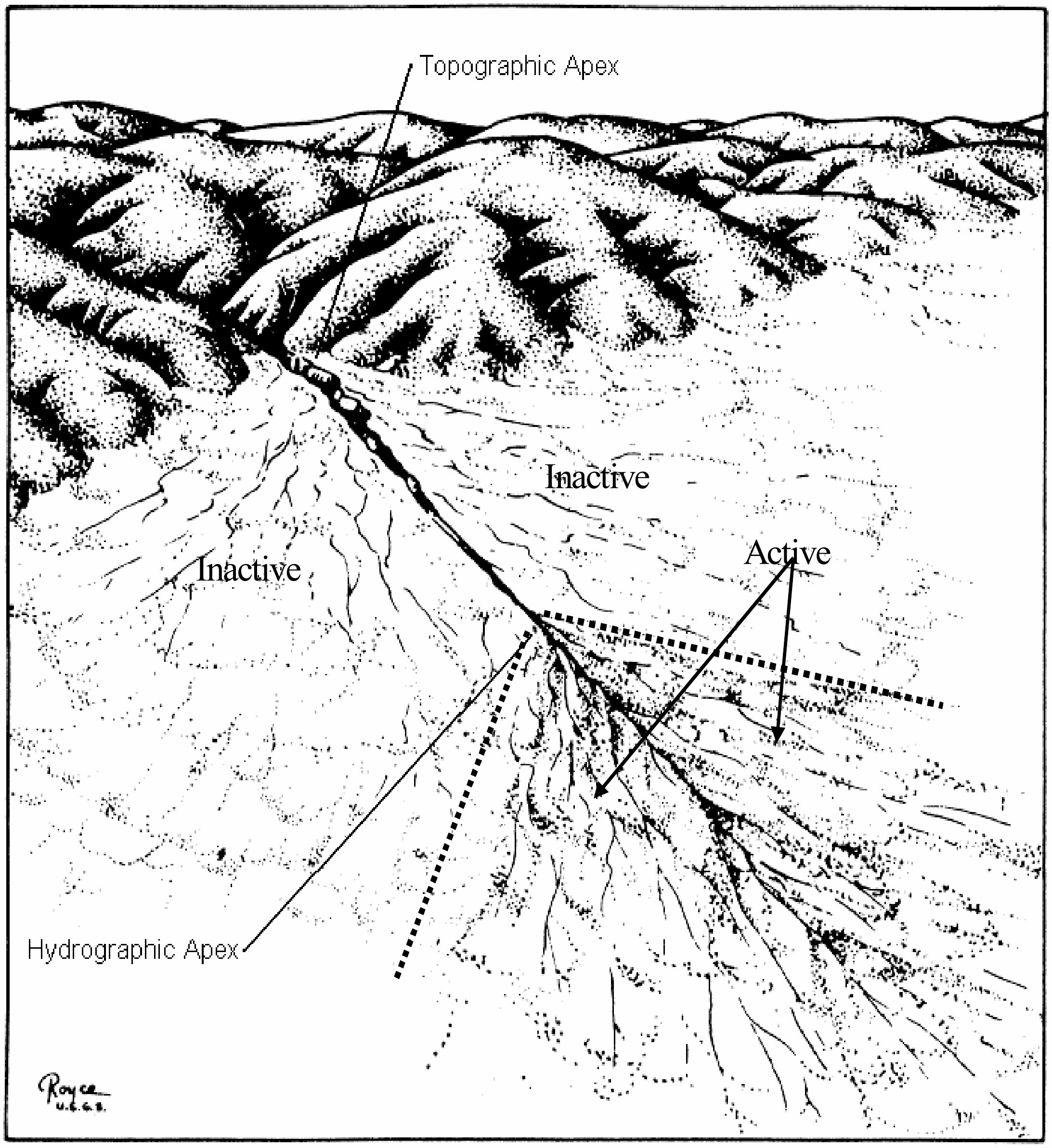

FIGURE CH12-101

CHAPTER 12

UNIQUE HYDRAULIC CONDITIONS

SECTION 2
MUD / DEBRIS FLOW

CHAPTER 12
UNIQUE HYDRAULIC CONDITIONS

SECTION 2
MUD / DEBRIS FLOW

TABLE OF CONTENTS

CHAPTER 12

UNIQUE HYDRAULIC CONDITIONS

SECTION 2

MUD / DEBRIS FLOW

2.1 INTRODUCTION

Presented in this section are requirements of engineering analyses, land management criteria, and mitigation measures for use in areas subject to mud and/or debris flow. Mud and debris flows are flowing mixtures of rock, earth, and other debris saturated with water. A mud flow is a mass of water and fine-grained earth materials that flows down a stream, ravine, canyon, arroyo, or gulch. If more than half of the solids in the mass are larger than sand grains, the event is called a debris flow. Both develop when water rapidly accumulates in the ground, such as during heavy rainfall or rapid snowmelt, changing the earth into a flowing mixture of mud. Mud and debris flows are a combination of fast moving water and a great volume of sediment and debris that surges down slope with tremendous force. They are similar to flash floods and can occur suddenly without time for adequate warning. When the drainage channel eventually becomes less steep, the liquid mass spreads out and slows down to form a part of a debris fan or a mud flow deposit. In the steep channel itself, erosion is the dominant process as the flow picks up more solid material. A drainage may have several mud flows a year, or none for several years or decades. They are common events in the steep terrain of Colorado and vary widely in size and destructiveness.

The likelihood of mud and debris flows is increased by actions that increase the amount of water or soils involved and are often caused by land mismanagement. Improper land-use practices on ground of questionable stability, particularly in mountainous canyon areas, can create and accelerate serious landslide problems. Removal of vegetation on steep slopes, dumping debris and fill in a mud flow path and improper road construction or earth moving can contribute to a mud flow. Mud and debris flow can also occur as a result of forest fire damage to trees, vegetation, and the soil structure.

Mud and debris flows become a serious threat to man-made works and human life when man inadvertently chooses to live in active mud flow areas. The best and easiest solution is to avoid building in hazardous locations prone to mud and debris flows. Therefore, the State of Colorado encourages avoiding development in areas subject to mud and debris flows.

Land-use zoning in partnership with professional inspections and proper design can alleviate many problems associated with mud and debris flows. Lack of suitable rural building sites and urban population pressure increase the uses of marginal building sites requiring greater investment in stabilization measures. Steep and weak hill slope areas require increased code and ordinance controls to reduce risks to life and property. Proper planning and implementation of mitigation measures can greatly reduce the risks.

2.2 ANALYSIS REQUIREMENTS

In areas subject to mud or debris flow, the following analysis elements should be conducted to delineate the exact boundaries of the hazard. This analysis will assist in developing mitigation measures necessary to reduce or eliminate the impacts of development and limit risk to life and property.

1. Slope/Topographic Analysis
   A slope/topographic map should be prepared and should depict contours at an interval of two feet or less. Additionally, the map should highlight areas of high geologic hazards, areas subject to mud and debris flow, and all significant steep slopes in the following categories:
   - greater than fifteen percent (15%) but less than or equal to thirty percent (30%) shall be designated Steep Slopes
   - greater than thirty percent (30%) shall be designated Very Steep Slopes
2. Vegetative Cover Description
   Vegetative cover should be denoted generally by type and density of vegetation. A more detailed tree/vegetation survey may be required if the site has significant or unusual vegetation, stands of trees, or wooded areas.
3. Soil Information
   Soil information should include as a minimum shrink-swell potential, elevation of water table, general soil classification, suitability for development, and erosion potential.
4. Geotechnical Report
   Geotechnical report should include as a minimum location of major geographic and geologic features, depth, types, and distribution of strata units (soil and rock) and their characteristics (strength, stability, etc.), structural features (folds, fractures, faults, etc.), and historic and potential mud and debris flow paths and other high-hazard areas such as mine shafts/tunnels, quarries and known rock fall paths, as well as other active processes and their rates or recurrence.
5. Hydrologic Report
   Hydrologic report shall include but not be limited to information on groundwater levels, natural and agricultural irrigation and drainage channels and systems, and base elevations in floodplains. A sediment yield and transport analysis may also be necessary.

2.3 MANAGEMENT CRITERIA

The Federal Emergency Management Agency (FEMA) has developed regulations for areas subject to mud and debris flow. It is recommended that all communities within the State of Colorado adopt and enforce these regulations. When FEMA designates an area Zone M, subject to mud and debris flow, on a community's Flood Insurance Rate Map (FIRM), the community shall adopt and enforce a grading ordinance or regulation which (i) regulates the location of foundation systems and utility systems of new construction and substantial improvements, (ii) regulates the location, drainage and maintenance of all excavations, cuts and fills and planted slopes, (iii) provides special requirements for protective measures including but not limited to retaining walls, buttress fills, subdrains, diverter terraces, benchings, etc., and (iv) requires engineering drawings and specifications to be submitted for all corrective measures, accompanied by supporting soils engineering and geology reports.

For areas subject to mud and debris flow, but not designated as such by FEMA, individual Colorado communities should apply the following:

1. Permits be required for all proposed construction or other development so that it can be determined if the proposed construction is within a mud or debris flow prone area.
2. Review of each permit application to determine whether the proposed site and improvements will be reasonably safe from mud and debris flows. Factors to be considered in making such a determination should include (i) the type and quality of soils, (ii) any evidence of ground water or surface water problems, (iii) the depth and quality of any fill, (iv) the overall slope of the site, and (v) the weight that any proposed structure will impose on the slope.
3. Require, if a proposed site and improvements are in a location that may have mud or debris flow, that (i) a site investigation and further review be made by persons qualified in geology and soils engineering, (ii) the proposed grading, excavations, new construction, and substantial improvements are adequately designed and protected against mud and debris flow damages, (iii) the proposed grading, excavations, new construction, and substantial improvements do not aggravate the existing hazard by creating either on-site or off-site disturbances, and (iv) drainage, planting, watering, and maintenance be such as not to endanger slope stability.

The City of Glenwood Springs and the USGS have developed substantial information and data on mud / debris hazards in Colorado as well as mitigation measures.

2.4 MUD/DEBRIS FLOW MITIGATION MEASURES

Mud and debris flow mitigation is defined as any sustained action taken to reduce or eliminate long-term risk to life and property from a mud or debris flow event. The primary purpose of mitigation planning is to systematically identify policies, actions, and tools that can be used to implement those actions. Implementing preventive mitigation measures, such as planting ground cover on slopes or installing flexible pipe fittings to avoid gas or water leaks, will help control or reduce the impact of mud and debris flows. Common mitigation measures include:

- Surface protection and vegetation
- Surface drainage ditches and storm drains
- Curtain drains, perforated plastic pipe
- Subsurface drainage
- Dewatering wells
- Horizontal drains
- Retaining Structures
- Soil stabilization
- Rip Rap buttress fills
- Retaining walls and drainage
- Piling
- Flood control walls
- Grading
- Slope contouring and terracing
- Removal and compaction or replacement of material
- Reduction of slope
- Debris basins
- Debris control channels

In most instances very little can be done to mitigate the mud flow process in the channel itself. Recognizing natural mud flow areas and avoiding them can prevent damage.

CHAPTER 12

UNIQUE HYDRAULIC CONDITIONS

SECTION 3
IRRIGATION FACILITIES

CHAPTER 12
UNIQUE HYDRAULIC CONDITIONS

SECTION 3
IRRIGATION FACILITIES

TABLE OF CONTENTS

CHAPTER 12
UNIQUE HYDRAULIC CONDITIONS

SECTION 3
IRRIGATION FACILITIES

3.1 INTRODUCTION

Many irrigation ditches and reservoirs traverse the State of Colorado. The ditches and reservoirs have historically intercepted storm runoff from rural and agricultural areas without significant risk. With the spread of urbanization, storm runoff has increased in rate, quantity, and frequency. The irrigation facilities can no longer be utilized indiscriminately as drainage facilities. These criteria will establish guidelines for the analysis and regulation of storm runoff and irrigation facilities.

3.2 TRANSMISSION FACILITIES

Irrigation transmission facilities (i.e. ditches and canals) shall not be used as storm water or flood conveyance facilities, unless specifically approved and designated by local governing jurisdictions and acknowledged by the irrigation facility owners. The flood conveyance capacity of irrigation facilities shall be acknowledged only by agreement between the facility owners and local governing jurisdictions.

Irrigation ditches are designed with relatively flat slopes and limited carrying capacity. As a general rule, irrigation ditches cannot be used as an outfall point for a storm drainage system because of these physical limitations. In addition, many ditches are abandoned after urbanization and therefore could not be successfully utilized for storm drainage without an agreement with a public entity for long term maintenance of the facility.

In certain instances irrigation ditches have been successfully utilized as outfall points for drainage systems, but only after a thorough hydraulic and hydrological analysis. Since the owner’s liability from ditch failure increases with the acceptance of storm runoff, the responsibility must be clearly defined before a combined system is approved.

The State of Colorado recommends the following guidelines:

1. Require new development to direct storm runoff into historic and natural drainageways and avoid discharge to irrigation canals or ditches except as required by water rights.
2. Where new development will alter patterns of storm drainage into irrigation ditches by increasing flow rates or volume, a written consent from the ditch company shall be submitted with the development application and approved by the local jurisdiction. The discharge of runoff into the irrigation ditch shall be approved only if such discharge is consistent with an adopted master drainage plan or substantiated by an adequate hydrologic and hydraulic analysis. Perpetuation of drain ownership and maintenance must also be established.
3. Where an irrigation ditch crosses a major drainageway within a developing area, the developer shall be required to design and construct the appropriate structures to separate peak storm runoff from ditch flows subject to the condition noted in Item No. 2.

4. Where irrigation ditches will serve as the outfall for a detention facility, the ditch water surface elevation shall be determined for the maximum irrigation flow of the ditch, and the storm water surface elevation shall be determined for the combination of the maximum irrigation flow and the 100-year storm water discharge of the detention facility.

3.3 STORAGE FACILITIES

If a publicly owned, operated and maintained dam is specifically designed and operated either in whole or in part for flood control purposes, then its effects shall be taken into consideration when delineating the floodplain below such a dam. The effects of the dam shall be based upon the 100-year flood.

If a dam is not specifically designed and operated, either whole or in part, for flood control purposes, then its effects, even if it provides inadvertent flood routing capabilities which reduce the 100-year flood downstream, shall not be taken into account, and the delineation of the floodplain below such dam shall be based upon the 100-year flood that could occur absent the dam's influence. However, if adequate assurances have been obtained to preserve the flood routing capabilities of such a dam, then the delineation of the floodplain below the dam may, but not need to, be based on the assumption that the reservoir formed by the dam will be filled to the elevation of the dam's emergency spillway and the 100-year hydrology can be routed through the reservoir to account for any attenuation effects.

As stated above, 'adequate assurances' shall, at a minimum, include appropriate recognition in the community's adopted master plan of: (1) the flood routing capability of the reservoir, as shown by comparison of the 100-year floodplain in plan and profile with and without the dam in place in order that the public may be made aware of the potential change in level of flood protection in the event that the reservoir flood routing capability if lost, (2) the need to preserve that flood routing capability by whatever means available in the event that the reservoir owners attempt to make changes that would decrease the flood routing capability, and (3) a complete Operations and Maintenance Plan.

The problem of dam safety and the associated hazards of emergency spillways have been brought to the attention of the public nationwide by recent dam failures, and is the subject of a National Dam Safety Program by the Federal Government. Jurisdictional dams are classified by the State Engineer as low, moderate, or high hazard structures when, in the event of failure, there is a potential loss of life. Dams presently rated as low or moderate hazard structures may be changed to high hazard classification if development occurs within the potential path of flooding due to a dam breach. In this case, the reservoir owners would be liable for the cost of upgrading the structure to meet the more stringent requirements for the high hazard classification. For this reason, the State of Colorado recommends new development be restricted below dams and reservoirs to outside of the high hazard areas.

3.4 DRAINAGE INTERACTION

In evaluating the interaction of irrigation ditches with natural drainages for the purpose of basin delineation, the ditch should not be utilized as a basin boundary due to the limited flow capacities of the ditch. The ditches will generally be flowing full or near full during major storms and, therefore, the adjacent basin runoff on the upper side of the ditch would flow across the ditch.

The State of Colorado recommends the following guidelines:

1. Assume that irrigation ditches are at full capacity when analyzing storm runoff.
2. Avoid discharge of runoff from urban areas into irrigation facilities except as required by water rights or where such discharge is in conformance with the approved master drainage plan, or where site constraints prohibits discharge alternative outfalls. Where site constraints exist, a variance shall be requested and must be approved by the respective local jurisdiction and the appropriate ditch company.

3.5 IRRIGATION DITCH CROSSINGS

When development occurs in areas adjacent to an irrigation ditch, a structure shall be constructed to separate peak storm runoff from the ditch flows. This can be achieved in one of three ways:

1. Complete separation of storm flow and irrigation flow. This type of control is often used for smaller ditches where combination of the flow would cause water quality problems. Examples of this type of structure are a flume crossing a gulch or a pipe under a ditch.
2. Discharge storm flows into the irrigation ditch and release excess flow to the drainage way at a point downstream utilizing a formal control structure. This type of control can be used where the ditch has adequate capacity to convey the storm flows and water rights on the stream in question. In addition, the structure requirements for this type of control may be less expensive than complete flow separation.
3. Discharge storm runoff into the irrigation ditch without returning the storm flow back to the drainageway. This type of control requires a thorough analysis of the ditch capacities and storm runoff peaks and volumes. It may also require a detention basin to reduce the runoff to the ditch capacities.

Each irrigation ditch crossing of a drainageway will have its own unique design and requirements and, therefore, a typical ditch crossing configuration does not exist. Where a ditch crossing structure is required, the applicant shall meet with local jurisdiction and the ditch company officials to develop the specific design requirements for the structure.

The designer/engineer is cautioned to verify that damage to downstream properties will not occur by bypassing of storm runoff.

3.6 IRRIGATION DITCH FAILURE

When development occurs adjacent to an irrigation ditch, the type of development anticipated downstream of the ditch shall be reviewed for public safety facilities such as dams, hospitals, fire stations, arterial roads, etc. The presence of such facilities shall require review of the ditch to determine the following:

1. Rate of flow, post-development, across the irrigation ditch. The irrigation ditch shall be assumed full in the analysis.
2. Likelihood that the irrigation ditch will fail when storm flows overtop. An analysis of the stability of the ditch is recommended.
3. Maximum capacity of the irrigation ditch.

4. Impacts downstream if the irrigation ditch were to fail at full capacity.

Each irrigation ditch will have its own unique design and requirements. If the ditch is not subject to overtopping failure, the design flood should be the larger of the maximum ditch flow and the design storm flow. If the ditch is subject to overtopping failure, the design flood should be the combined maximum ditch flow and the peak storm flow. Failure of the ditch should be assumed to occur at the point resulting in the greatest impact downstream unless evidence supporting a different failure point is provided.

The local controlling governmental agency may, at its discretion, require ditch failure analysis under additional circumstances.

3.7 MUTUAL AGREEMENTS

The key to successful use of irrigation ditches for flood conveyance purposes is the establishment of a “Mutual Agreement” for perpetual ownership and maintenance of the irrigation ditch. The City of Fort Collins and the UD&FCD both have several example agreements which may be used as a basis for establishing a “Mutual Agreement”.

CHAPTER 12

UNIQUE HYDRAULIC CONDITIONS

SECTION 4

ICE JAMS

CHAPTER 12
UNIQUE HYDRAULIC CONDITIONS

SECTION 4
ICE JAMS

TABLE OF CONTENTS

CHAPTER 12
UNIQUE
HYDRAULIC
CONDITIONS

SECTION 4
ICE JAMS

CHAPTER 12
UNIQUE HYDRAULIC CONDITIONS

SECTION 4
ICE JAMS

4.1 INTRODUCTION

Ice jams are an accumulation of ice in a river, stream, or other flooding source that reduces the cross-sectional area available to carry the flow and increases the water surface elevation. A rise in stream stage will break up a totally frozen river and create ice flows that can pile up on channel obstructions. Ice usually accumulates at a natural or manmade obstruction or a relatively sudden change in channel slope, alignment, or cross-section shape or depth. The jammed ice creates a dam across the channel over which the water and ice mixture continues to flow, allowing for more jamming to occur. Backwater upstream from the ice dam can rise rapidly and overflow the channel banks. Flooding moves downstream when the ice dam fails, and the water stored behind the dam is released. At this time the flood takes on the characteristics of a flash flood, with the added danger of ice flows that, when driven by the energy of the flood wave, can inflict serious damage on structures. Ice jams are common in locations where the channel slope changes from relatively steep to mild, and where a tributary stream enters a large river.

In Colorado, where rivers can develop relatively thick ice covers during the winter, ice jams can contribute significantly to flood hazards. Although discharges may be low relative to a free-flow flood, the stages of ice jam flooding may be among the highest on the record. Ice jams typically occur repeatedly in the same locations and ice jam flooding tends to be very localized and highly site specific.

4.2 FORMATION OF ICE JAMS

Ice forms in freshwater bodies whenever the surface water cools to 32^{o} F, or slightly lower. There are four basic types of ice: sheet ice, frazil ice, fragmented ice, and brash ice.

A) Sheet ice forms in calm water, such as slow moving river reaches with velocities less than 1.5 ft/sec, lakes, or reservoirs. Sheet ice may contribute to ice jams by providing a barrier to ice moving through or by moving into a body of water where sheet ice is present.

B) Frazil ice forms in highly turbulent, supercooled water and consists of small ice particles. Frazil ice is created where very cold air is mixed with water causing the water temperature to fall below the freezing point. As the water moves downstream small particles of ice are formed and join together to form flocs, which eventually rise to the surface. The flocs may form larger aggregations called frazil pans or accumulate on ice or objects in the water. Frazil ice may contribute to ice jams by supplying ice to the jam or by building up frazil pans to the point that a solid layer of surface ice is formed. Frazil ice may also accumulate under sheet ice to form hanging dams, which may then become initiation points for ice jams.

C) Fragmented ice is made up of pieces of ice. Fragmented ice originated as sheet ice or frazil pans, which was subsequently broken into pieces.

D) Brash ice is an accumulation of fragmented ice frozen together into pieces up to approximately 6 feet in the maximum dimension.

Flooding occurs when the ice jam builds to the point that the existing flow or an increase in flow causes flooding due to backwater effects or when the ice jam suddenly releases water held behind the jam causing flooding downstream.

Ice jams may be categorized into four main types: freeze-up jams, break-up jams, floating jams, and grounded jams.

A) Freeze-up jams are associated with the formation and accumulation of frazil ice, which eventually forms a continuous ice cover. Freeze-up jams typically occur during early winter to midwinter. Floating frazil ice begins to accumulate when it reaches a change in water surface slope from steep to mild, an obstruction, or some other hydraulic occurrence which slows or stops the movement of the ice. A jam forms when the ice stops moving, forms a horizontal arch across the stream channel, and begins to accumulate additional ice.

B) Break-up jams are frequently associated with rapid increases in runoff and rises in river stage, resulting from rainfall and/or snowmelt. Break-up jams usually occur during late winter or early spring. Breakup jams are composed primarily of fragmented ice, formed from sheet ice or a frazil jam. The fragmented ice moves downstream until it reaches intact ice cover of sufficient strength to arrest the movement of the ice, a change in water surface slope from steep to mild, an obstruction, or some other hydraulic occurrence which slows or stops the movement of the ice. The ice may then consolidate or freeze in place. If the flow subsides, as is typical of mid-winter thaws, the ice pieces may become grounded causing future problems when flows increase during a later thaw.

C) Floating jams are considered to be those where the ice is not grounded to the channel bottom and significant flow takes place beneath the ice cover. Floating-type jams are typical of deeper rivers.

D) Grounded jams are characterized by an ice cover that is partially grounded to the bed of the channel, with most flow being diverted into the overbank and floodplain areas. Grounded jams are typical of shallow, confined stream sections.

4.3 OCCURRENCES OF ICE JAMS

Ice jams in Colorado typically can occur only in areas subject to prolonged and sustained temperatures of sub-freezing levels with durations exceeding two weeks or more.

Ice jams start forming at locations in a stream where transport of ice is restricted due to hydraulic changes such as obstructions, changes in channel shape, decrease in water surface slope, and existing ice. Channel bends may exacerbate ice jamming, but typically require other factors be present to initiate a jam. Other factors which do not normally initiate jams, but which may contribute, are islands, sandbars, and gravel deposits. These features are normally indicative of a decrease in sediment carrying capacity and reflect the presence of hydraulic features conducive to the formation of ice jams.

The most common location for the formation of an ice jam is at variations in stream slope from relatively steep to mild. The decrease in water surface slope causes a loss in momentum of the ice being transported and can result in an arch of ice across the stream surface. Additionally, sheet ice may form across the slow moving water providing an initiation point for the ice jam. Pools, ponds, and reservoirs reflect a decrease in water surface slope and are therefore common locations for ice jams.

Additional locations where ice jams can form are confluences, sites of natural or artificial obstructions, and downstream of hydraulic structures with varied outflow. Stream confluences can initiate jams when the smaller tributary has ice cover that breaks up before the ice cover on the main branch. The fragmented ice of the smaller tributary is transported downstream to the solid ice cover of the main branch, causing an ice jam. Obstructions may collect fragmented ice or act as points of initiation for ice formation. Obstructions may include fallen trees, culverts, pilings, and weirs. Hydraulic structures whose operation increases or decreases an existing flow rate may cause sheet ice downstream to fragment, initiating an ice jam.

4.4 IMPACTS OF ICE JAMS

Ice jams can cause damage in several ways and by several different mechanisms. Design of structures and facilities where ice jams are possible should take these possibilities into account.

A) Backwater: Ice jams cause increases in water surface elevation upstream, resulting in flooding and ice damage.

B) Ice Jam Failure: Flooding problems are caused if an ice jam, having created an increased pool elevation behind the jam, fails suddenly releasing a flood wave downstream transporting fragmented ice. The flood wave may cause downstream flooding and scour and the fragmented ice can cause impact damage to structures as well as initiating other ice jams.

C) Structural Impacts: If an ice jam occurs at a bridge or other structure it can exert additional pressure on the structure. The additional ice will increase the surface area and the amount of flow in contact with the structure. The ice jam can also increase the velocities around the footings and supports of the structure. If the ice cover is solid and the water surface elevations increase, the ice will rise. This has the potential to lift the bridge off its supports.

D) Reduce Hydraulic Head: Ice jams may also cause problems to facilities requiring a minimum water surface elevation change to operate, such as hydroelectric dams. Ice jams downstream of the facility may raise the water elevation at the foot of the facility to the point that the facility is unable to operate or must operate at reduced efficiency levels.

4.5 PREDICTION OF ICE JAMS

There is a lack of reliable and widely applicable methodology for predicting where ice jams will occur. Ice jams typically occur repeatedly in the same locations and ice jam flooding tends to be very localized and highly site specific. Without a history of ice jam flooding, it is difficult to determine if a specific site is at risk. This leaves the planner with the task of deciding if ice jams are possible on a given stream reach. The planner should take into account the elements necessary for ice formation and the factors contributing to ice jam formation to decide whether a location may be subject to ice jams. Specifically, it should be considered whether there exists a supply of ice, either at the location or upstream of the location, and a possible trigger for ice jam formation at the location under consideration. Knowledge of the area, the typical and extreme weather events, and the flow characteristics of the stream are basic starting points for any investigation. The planner should then conduct inquiries of local officials, past and present, historians, news organizations, and local residents, if necessary. Additional resources may include the following agencies: U.S. Geological Survey (USGS), Bureau of Land Management (BLM), Cold Regions Research and Engineering Lab (CRREL) of the U.S. Army Corps of Engineers, Federal Emergency Management Agency (FEMA), and the National Weather Service (NWS).

4.6 ANALYSIS APPROACHES

Different methods may be used for establishing flood elevations in areas subject to ice jams, depending on the availability of data and the nature of the ice jam phenomena that occur at the site of interest. The Federal Emergency Management Agency (FEMA) currently recommends the methods outlined herein. They are applicable primarily to stationary-type ice jams that occur during periods of ice break-up.

The approaches in the following subsections are based on the development of stage-frequency relationships for two different populations (ice jam flood stages and free-flow flood stages), which are then combined into a single composite frequency curve for flood stages at a site under study. Depending on the availability of ice jam information, ice jam stage-frequency relationships may be determined directly or indirectly.

4.6.1 DIRECT APPROACH

If sufficient data exist at the site of interest, an ice jam stage-frequency distribution shall be established directly by analyzing the historical ice stage data. This approach is preferred where ice jam stages are available for three or more significant events (overbank flooding) that span more than a 25-year period of record and where hydraulic conditions have not changed appreciably since those events.

Limited data on historical ice jam stages are usually available at ungaged locations, but the data can be obtained from a number of ways, including:

- Community officials
- Resident recollections
- Newspaper accounts
- High-water marks
- Tree damage or scars
- Vegetation trim lines
- Disturbed bank material

If historical records of stage are sufficient, a graphical frequency analysis may be used by computing plotting positions and fitting a frequency curve on probability paper. Because of their simplicity, Weibull plotting positions are recommended.

If the study area includes a gaging station where historical ice jams have occurred, a stage-frequency analysis using the stage data at the gaging station may be performed. This data is published by the U.S. Geological Survey and other agencies. The annual maximum stage can occur as a result of either a free-flow event or an ice jam event. For the ice jam events, the annual maximum peak stage can occur at a different time than the annual maximum peak discharge.

If detailed data are available, there are two approaches for the direct analysis of stage data: (1) annual event series and (2) annual maximum series. The annual event series approach is used when data is available for both the maximum peak stage during the ice jam season and the maximum peak stage during the free-flow season for each year (two values per year). The annual maximum series approach is used when only the data for the annual maximum peak stages are available.

In both approaches, frequency curves for the ice jam events and the free-flow events are established and then combined to determine the percent chance that a given stage will be exceeded in a year. Weibull plotting positions are preferred for determining the individual stage-frequency curves. However, when there are more than 10 years of ice jam or free-flow stages, a frequency distribution such as the log-Pearson Type III may be fit to the stage data or their logarithms to help define or extend the stage-frequency curve based on plotting positions.

4.6.2 INDIRECT APPROACH

Where available data are insufficient to establish a stage-frequency distribution directly, an indirect approach to ice jam stage-frequency analysis may be used.

Establish a free-flow stage-frequency distribution for each cross section by using standard backwater modeling to establish stage discharge relationships. Usually, the four standard (10-, 2-, 1-, and 0.2-percent-annual-chance) flood discharges will provide sufficient points for establishing the stage-frequency curve for each cross section on normal probability paper.

Separate the water year into an ice jam season and a free-flow season based on historical occurrence of ice jams in the region and, in particular, in the flooding source that is the subject of the study. For ungaged streams, establish seasonal discharge frequency relations by performing a regional analysis of seasonal flows for the gaged streams in the region. Usually, the establishment of regional seasonal discharge drainage area relations will be sufficient for this purpose.

Use standard hydraulic techniques to establish corresponding stage-frequency curves for each cross section in the reach where ice jams are to be considered. For ice jam analysis, this is typically accomplished using the ice cover option In the U.S. Army Corps of Engineers HEC-RAS computer program. This analysis takes into account thickness of the ice, roughness coefficients "n" for the underside of the ice cover, and specific gravity of the ice. The recommended ranges for "n" values are from 0.015 to 0.045 for unbroken ice and from 0.04 to 0.07 for ice jams. The specific gravity of normal ice is approximately 0.92 and is the recommended value for this analysis.

Calibrate for floating type jams by assuming equilibrium ice thickness at the location where the ice jam stage-frequency curve is needed and use a combination of discharge, equilibrium ice thickness, and roughness that would correspond to that stage. Grounded type jams should assume complete blockage of the main channel at the point of obstruction. The ice cover option can be used in HEC-RAS to estimate corresponding ice jam stages upstream and downstream.

Establish a stage-frequency curve for the ice jam and free-flow events by plotting the stages from the HEC-RAS analyses at each cross section. Not every flood event during the ice jam season is affected by ice. If sufficient ice jam data are available, then the study can incorporate the fraction of time that ice jam season peak stages are affected by ice in the analysis. If the discharge frequency relation in the ice jam season is independent of ice conditions, then the flood discharges are essentially the same for those years when ice jams occur and when they do not occur.

Under these conditions, develop water surface profiles for ice affected and free-flow conditions in the ice jam season. Combine the stage-frequency curves with the following equation:

$$P(s) = (P(sw) * P(si = \text{ice jam event}) + P(so) * P(si = \text{free-flow event})) + P(sq)$$

where

P(sw) = Probability of exceeding a given stage "s" in the ice jam season developed using the discharge frequency relationship for the ice jam season and ice affected hydraulic conditions

P(si = ice jam event) = Fraction of years during the ice jam season that peak stages are affected by ice jams

P(so) = Probability of exceeding a given stage "s" in the ice jam season developed using the discharge frequency relationship for the ice jam season and free-flow hydraulic conditions

P(si = free-flow event) = Fraction of years during the ice jam season that peak stages are free-flow events

P(sq) = Probability of the annual maximum stage exceeding a given stage "s" in the free flow season

The assumption in this equation is that the conditional distribution of peak discharges for the ice jam season is the same for ice affected and free-flow conditions. If ice jams only occur when peak discharges are large or, conversely, if large peak discharges do not occur under free-flow conditions, this equation does not apply.

4.7 MITIGATION OF ICE JAMS

Mitigation is defined as any sustained action taken to reduce or eliminate long-term risk to life and property from a hazardous event. The primary purpose of mitigation planning is to systematically identify policies, actions, and tools that can be used to implement those actions. Implementing preventive mitigation measures, such as (i) providing additional storage or flow paths for water during ice break-up, (ii) change the location of the potential ice jam, and (iii) reduce the amount of ice available to cause an ice jam, will help control or reduce the impact of ice jams. Common mitigation measures include:

4.7.1 ADDITIONAL STORAGE

Areas that are considered to be at risk for ice jams may set aside additional storage volumes beyond what would be considered for other flood events. One recommendation adopted by some local governments is to add an additional foot of freeboard on top of the standard 100-year flood level. The additional freeboard increases the volume available for storage and ensures that structures most at risk of flood damage during an ice jam will be elevated or otherwise flood-proofed.

4.7.2 ALTERNATE FLOW PATHS

Construction of channels accepting flow only during high water events to carry flood waters around an ice jam location is one method of maintaining flow capacity during an ice jam. Alternatively, small streams may be piped around an ice jam location. Piping bypasses the ice jam, reduces air entrainment, and, if buried, may warm the water flowing through the pipe. Care should be taken that the intake of the secondary channel or pipe is above the jam location and ice will not block the entrance.

4.7.3 ICE RETENTION

Ice retention prevents ice jams from forming downstream. Ice retention falls into two categories: sheet ice stabilization and ice interception. Most methods at least partially overlap the two categories. Methods in use at various locations include: nets, booms, piers, piles, dolphins (groups of piles), weirs, permanent and inflatable dams, large rocks, rock cribs, ice islands, groins, bridge piers, and tower foundations.

Dams promote sheet ice in the reservoir and store frazil ice from upstream reaches reducing the amount of ice downstream of the dam. Nets of wire rope, chain-link fencing, or even cables with vertical rails can act as frazil ice collectors and initiate an ice dam which then forms sheet ice behind the net. Care should be taken with temporary dam structures as they may promote scour of the stream bed and/or banks as the ice builds and flow is forced to the edges of the structure. Some installations include armoring of the bed and banks at the point of installation.

Ice nets promote ice growth and promote the formation of sheet ice in water velocities up to 3 ft/sec. In addition to promoting sheet ice, these structures may aid in controlling breakup ice from moving downstream until the downstream reaches are clear. Delay of the movement of breakup ice lowers the probability of the ice forming ice jams as it moves downstream.

Breakup control structures will, in general, require the capability of resisting greater forces from momentum transfer as upstream ice arrives at the structure. Additionally, if an ice jam is initiated, the resulting encroachment of ice on the banks and bed may result in unacceptable levels of scour.

Ice islands, dolphins, and booms may be used to stabilize sheet ice to prevent its breakup into fragmented ice and causing ice jams or interfering with shipping or other stream operations. Booms may be used to prevent lake sheet ice from entering stream channels. Booms promote the formation of sheet ice and are effective at low surface velocities ($\leq$ 2.3 ft/s), low energy slopes, and low Froude numbers ($\leq$ 0.08).

Piers may be used to initiate sheet ice formation upstream of areas of potential ice jam problems.

4.7.4 PREVENTING ICE FORMATION

Ice formation may be prevented by removing one of the two elements necessary for ice formation: water or cold air. Elimination of the water, (i.e. retention of all or most of the water behind a dam) is likely not practical. However, the flooding of upstream rapids and riffles will prevent the entrainment of cold air and eliminate frazil ice formation. This technique has been used in several instances to reduce the amount of frazil ice reaching a hydroelectric dam or other area of concern. Another method of accomplishing this is the installation of some sort of temporary dam to flood the rapids and promote the formation of sheet ice.

4.7.5 PHYSICALLY REMOVING ICE

The removal of ice from the stream may be accomplished by several techniques; but usually requires an annual commitment in personnel and materials. Physically removing ice by dragline or backhoe is practical only where the ice is accessible from the banks or a bridge and there are overbank areas where the ice may be stored until it thaws.

4.7.6 BREAKING ICE

Although breaking the ice is often the first method to be thought of for dealing with an ice jam, usually with explosives, this is a hazardous and sometimes disastrous method. Care must be taken to work from the downstream to the upstream end of the jam to avoid fragmented ice re-initiating the ice jam. If too much ice is released into the stream at once fragmented ice may cause an ice jam downstream in a new location or a flood wave may result which could cause damage downstream. Various methods to break the ice include: a wrecking ball, explosives, or an excavator equipped with a jack-hammer. A Ditch-Witch to cut the ice or an auger to open holes in the ice which promote melting and weakening of an ice sheet have both been used to control the breakup of sheet ice.

4.7.7 MELTING ICE

The use of solar heating, air, or water to promote slow melting of ice sheets ahead of a spring thaw has been successful, in many locations, in preventing ice jams caused by fragmented ice and in reducing the volume of fragmented ice. Since subsurface water has temperatures above freezing the use of water currents can cause melting of ice while surface temperatures are still below freezing. One method of encouraging melting is to auger holes through the ice. The hole may freeze over, but the opening in the bottom of the ice will expand if there is a flow of water past the opening. By drilling holes at regular intervals, large areas of ice may be weakened. Similar in effect is the use of a bubbler system. Placing a bubbler on the bottom of a lake or reservoir will cause water currents against the bottom of the ice sheet. The water currents will melt the ice sheet and may cause enough weakening to prevent an ice jam where a stream enters the water body. Warm discharge water has also been used to melt sheet ice. The darkening of ice using crop-dusting aircraft to lay dark dust or hydro-seeding machinery to spray leaf mulch may be used to promote melting of ice. There are references which provide details on methods, conditions, and optimum materials available from CRREL and others.

CHAPTER 12

UNIQUE HYDRAULIC CONDITIONS

SECTION 5

DRAINAGEWAY BUFFER ZONES AND SETBACK LIMITS

CHAPTER 12
UNIQUE HYDRAULIC CONDITIONS

SECTION 5
DRAINAGEWAY BUFFER ZONES AND SETBACK LIMITS

TABLE OF CONTENTS

CHAPTER 12
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SECTION 5
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5.1 INTRODUCTION

This chapter is devoted to setbacks from waterbodies which might be necessary and more restrictive than simply regulating to 100-year floodplain limits. Channel migration and bank erosion can constitute a greater hazard than mere overbank flooding. Typical floodplain studies assume a "fixed bed" channel that does not acknowledge the potential for the river channel to change vertically or horizontally. However, there may be a dramatic difference between the regulatory floodplain and the geomorphic floodplain, which considers where the river has been in the past and where it could move in the future.

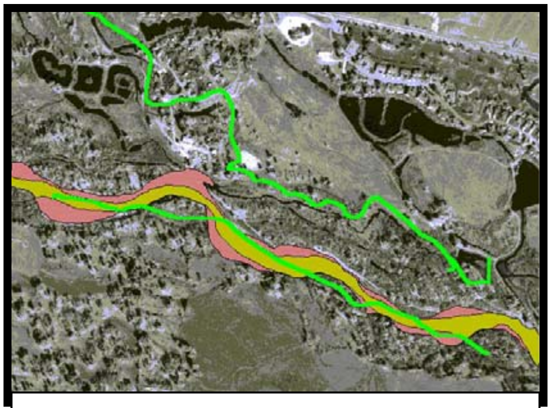
This roadway was outside the 100-year floodplain, but nonetheless, still at risk to flood hazards.

Delineation of floodplains typically assumes rigid boundaries, meaning there is no change to the channel bed and banks during a major flood. This is not a realistic assumption for many Colorado waterways. The physical processes involved with channel migration and the analysis of those processes are inherently complex. Anticipating erosion and sedimentation is very difficult due to many variables, including:

- Non-homogeneous geology
- Variable soil cohesion
- Variable water velocity
- Variable applied shear stress
- Hydrology
- Vegetation
- Debris blockage
- Bedload
- Utility crossings
- Structures

It is prudent to consider the principles of fluvial geomorphology, along with hydraulic engineering, in floodplain management. By linking the river morphology (present form and conditions) and the geomorphic history (past conditions) of drainageways with hydrologic and hydraulic data, prediction of future river behavior during a flood may be increased.

Since it is neither practical nor desirable to hard-line all channels to prevent channel movement, limiting how close development can occur next to the channel may minimize potential property damage. By incorporating into development criteria ***buffer zones*** and ***setback limits*** which account for potential channel migration along with floodplain delineations, future flood hazard risk to development can be reduced. This setback is sometimes referred to as the ***prudent line*** since without major channel stabilization measures it would not be prudent to construct property improvements due to the potential for damage associated with flooding and bank erosion.



This aerial photograph of the Roaring Fork River show how the channel has moved over time. Yellow and red signify the location of the low flow channel before and after flooding in 1995. The green lines delineate the regulatory floodplain. The low flow channel actually migrated laterally beyond the limits of the regulatory floodplain.

5.2 CHANNEL INSTABILITY

Although these structures may be outside the 100-year floodplain, it would not be prudent to develop this close to an unstable channel. Erosion buffer zones and setback limits from waterbodies preserve natural riparian function and reduce flood hazard risks.

Rivers change course and experience erosion and deposition over time even under natural conditions. Introduce urbanization and channel instability can dramatically increase due to changes in runoff, sediment supply and encroachments. River dynamics consist of a continual balancing of the river’s energy with resistance to motion of the riverbed and bank materials. The dynamic nature of streams is often ignored, not noticing or understanding the changes that may be occurring over time. For example, changes in runoff, changes in sediment types or amounts, changes in the makeup of streambed or banks, changes in channel shape, and even fallen trees may cause instability or channel movement while the river adjusts to new conditions. Those adjustments may take the form of changes to channel shape, size or location, stream steepness, velocity, riverbed or bank makeup, or other parameters. Depending on site-specific conditions, stability may be reestablished quickly or may be measurable only in terms of geologic time. In naturally stable streams, there is a general balance between sediment erosion (scouring of the bed and bank) and sediment deposition (the accumulation of particles on the riverbed). This balance is continually changing but the adjustments in stable channels are relatively minor, and vegetation can improve stability of the channel. Although a stable channel is in equilibrium, continual natural adjustments result in a condition referred to as “dynamic equilibrium.”

When the natural balance of a stream is disrupted by rapid changes from human or natural causes, the channel will attempt to achieve a new equilibrium, rapidly or over time. The best management approach with respect to man-induced changes is to regulate land uses so as to recognize and design mitigation of stream stability impacts before allowing activities which may contribute to stream instability. When land use activities cause stream instability it may not be appropriate to wait for an impacted stream to repair itself and reestablish equilibrium through natural processes. This chapter is intended to help communities understand and protect themselves from instability, and provide recommendations to maintain stability or to return a destabilized river to a stable condition in the shortest reasonable time and maintain a stable state thereafter.

5.3 DYNAMIC EQUILIBRIUM

Under natural steady conditions the river dynamic equilibrium between channel resistance and energy of water flow is established over many years. Alterations to a river channel disrupt this dynamic equilibrium and cause changes to the channel hydraulic parameters. Encroachment into or near the river floodplain and riparian zone can have long-lasting impacts on the stream system by disrupting characteristics such as sediment load, stabilizing vegetation, floodplain boundaries, floodplain storage, channel resistance, runoff, diversion of flow, channel pattern and geometry. Adjusting even one parameter can upset the balance between these channel properties. Under balanced conditions rivers achieve stability by shaping and adjusting the channel bed and banks to accommodate the range of flows naturally occurring in the drainage basin. Left alone, a river will eventually regain a dynamic balance between river velocity, flow depth, gradient, and channel roughness.

Under conditions of dynamic equilibrium, a stream’s energy is at a level that allows sediment loads entering a stream reach to equal those leaving it. If more free energy is available than is expended by the flow, the principle of continuity requires changes in some or all hydraulic variables, such as width and depth of flow, slope, velocity and flow resistance. Morphologic changes result which lead to changes in sediment load. Whatever process occurs, it is directed toward attainment of a new equilibrium between available and expended energy.

5.4 DEFINING CHANNEL INSTABILITY

Channel instability can be characterized as:

1. **Vertical Instability**, leading to changes in the channel bed elevation level by deposition of material (aggradation) or erosion of the bed material (degradation). This is a major problem at bridges where the foundations become exposed; at utility crossings where pipelines can be washed away; or at critical floodplain areas where water can overtop the riverbanks.

2. **Lateral Instability**, where erosion or deposition at the channel banks causes the low-flow channel location to migrate horizontally. This can drastically affect property and infrastructure, and is the most easily recognizable result of channel instability.

Instability occurs when the channel migrates laterally, or the channel bed is raised or lowered, thereby forcing changes in the flow hydraulics, especially during flooding conditions. This instability can lead to many negative impacts including river encroachment on property and buildings, floodplain alteration, exposure of buried utility lines, scouring around bridge piers, increased river sediment load, weakened bank stability, diminished aquatic habitat, destroyed wetlands and riparian vegetation, and reduced recreational opportunities. Development and river system coexistence are promoted when channel adjustments and fluctuating river conditions are more controllable and predictable. Channel restoration is necessary when conditions have caused a river to become unstable to the point where it becomes unmanageable.

Individual efforts to control and restrict the river in one location may cause subsequent damage in another area, and an extended reach may become unstable. As natural channel migration and sediment transport processes continue as part of the river's effort to re-establish dynamic equilibrium, the river widens or incises with each subsequent flood. The massive transport of bed and bank material that can occur during flood events may significantly alter the river's alignment and geometry. Attempts to stabilize the channel by restricting it to a narrow corridor may result in more instability and uncontrolled damage to property.

5.5 DRAINAGEWAY SETBACK ZONES

The intent of setback criteria is to preserve riparian corridors to help protect the physical, chemical and biological integrity of waterbodies from adverse water quality and quantity impacts. Preservation of riparian corridors along waterbodies will help promote streambank stability and prevent increased stream temperature, accelerated loading of nutrients and sediments and other pollutants. Vegetation in the riparian corridor plays a critical role in the food chain for aquatic organisms. The purpose of the criteria is to protect these functions of the riparian corridor. Current scientific research indicates that a "tiered approach" to waterbody buffers is more effective than a single setback. This approach provides more flexibility on the location and nature of disturbance in the riparian zone.

A tiered approach to waterbody setbacks is recommended to apply to all activities requiring development approvals. Where the development approval is for the "redevelopment" of an existing, nonconforming use, every effort should be made to provide for the restrictive inner buffer zone portion of the buffer system.

5.5.1 RESTRICTIVE INNER BUFFER

A minimum setback of twenty five feet (25') measured horizontally from the typical and ordinary high water mark in average hydrologic years on each side of a waterbody or field delineated wetland is required. Earth or vegetation disturbance is restricted within this inner buffer zone. Irrigation and water diversion facilities, flood control structures, culverts, bridges and other reasonable and necessary structures requiring some


Development of this property along the upper Roaring Fork River maintained the floodplain and screening vegetation.

disturbance within this setback may be permitted. The following items are examples of actions that are not allowed within the restrictive inner buffer zone:

1. Placement of material, including without limitation any soil, sand, gravel, mineral, aggregate, organic material, or snow plowed from roadways and parking areas;

2. Construction, installation, or placement of any obstruction or the erection of a building or structure;

3. Removal, excavation, or dredging of solid material, including without limitation any soil, sand, gravel, mineral, aggregate, or organic material;

4. Removal of any existing live vegetation or conducting any activity which will cause any loss of vegetation, unless it involves the approved removal of noxious weeds, non-native species, dead or diseased trees;

5. Lowering of the water level or water table by any means, including draining, ditching, trenching, impounding, pumping or comparable means; and,

6. Disturbance of existing natural surface drainage characteristics, sedimentation patterns, flow patterns, or flood retention characteristics by any means including without limitation grading and alteration of existing topography. Measures taken to restore existing topography to improve drainage, flow patters, flood control, etc. must be approved.

5.5.2 VARIABLE OUTER BUFFER ZONE

Earth and vegetation disturbance within this variable buffer may be limited where necessary to protect the integrity of the waterbody or special site specific features. For a specific site, this variable buffer may range from zero (0') to seventy-five feet (75') beyond the outer edge of the restrictive inner buffer zone described above (i.e. up to 100' beyond the high water mark of the waterbody during average hydrologic years or wetland boundary.) The width of this variable outer buffer zone may be undulating across a piece of property in order to in order to provide protection to site specific features. Site specific features that could trigger the need for either an outer buffer zone, equivalent mitigation, or a combination of outer buffer zone and mitigation include:

This property was constructed without setback limits and although it may have a finished floor above the floodplain, it may certainly be at risk to damage if the bank begins to erode. Reducing risk by rock lining the bank has adverse environmental impacts.

1. Steep slopes draining into the waterbody or wetland;
2. Highly erodable soils are present;
3. Presence of unstable streambank conditions;
4. The proposed use of the property presents a special hazard to water quality (e.g., storage or handling of hazardous or toxic materials);
5. The area is needed to protect trees, shrubs, or other natural features that provide for streambank stability, habitat enhancement for aquatic environments, riparian area protection, or to maintain pre-development riparian plant or animal communities;
6. The area provides habitat for plant, animal, or other wildlife species listed as threatened or endangered by the United States Fish and Wildlife Service;
7. The area provides habitat for plant, animal, or other wildlife species listed by the State of Colorado as rare, threatened, or endangered, species of special concern, or species of undetermined status;
8. The area is within the 100-year floodplain;
9. The area is needed to prevent or minimize flood damage by preserving storm and flood water storage capacity;
10. The area is needed to protect fish spawning, breeding, nursery and feeding grounds; or,
11. The area is needed to preserve areas of special recreational, historical, archeological, scenic, or scientific interest.

5.6 DELINEATION OF BUFFER ZONES

Site plan submittals shall include delineation of all applicable buffer zones. These boundaries should also be shown on all clearing, grading and erosion control plans. Because the variable outer buffer zone is site specific, applicants are expected to submit rationale for the size of this buffer zone and identify proposed mitigation measures to be used at the site. Engaging the expertise of a geomorphologist is recommended.

Approaches to buffer zone delineation vary. Regional studies are valuable because they analyze the stream system as a whole. Some regional studies have been completed on the geomorphologic floodplain for drainageways such as Fossil Creek in Fort Collins, the Roaring Fork River near Basalt, and Fountain Creek near Colorado Springs. Site specific studies can be completed, but should examine major trends and natural processes on the drainageway. Stabilizing a channel with rock riprap as a solution to channel stability destroys riparian habitat and natural waterway function, and should be considered only as a last resort.

Field reconnaissance of the watershed and stream system is mandatory. A hydraulic model is highly recommended to quantify hydraulic conditions during a flood. A quantitative study may be completed through a sediment transport analysis and calculation of applied shear stress relative to resistance of the bed and banks. A qualitative analysis can be completed by studying historic aerial photographs to determine where the channel has migrated over time and where it may be headed in the future.

CHAPTER 12

UNIQUE HYDRAULIC CONDITIONS

SECTION 6
TWO-DIMENSIONAL MODELING

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SECTION 6
TWO-DIMENSIONAL HYDRAULIC MODELING

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 12
UNIQUE HYDRAULIC CONDITIONS

SECTION 6
TWO-DIMENSIONAL HYDRAULIC MODELING

6.1 INTRODUCTION

Two-dimensional modeling is sometimes needed to analyze the hydraulics of certain complex situations that do not lend themselves to the assumptions of one-dimensional modeling. This section presents an overview of two-dimensional hydraulic modeling. It describes common situations that may benefit from two-dimensional modeling. This section also identifies the readily available types of two-dimensional models and the specific modeling programs that are currently accepted by FEMA for nationwide use.

6.2 OVERVIEW OF TWO-DIMENSIONAL MODELING

A hydraulic model is, in general, a mathematical approximation of an actual hydraulic system. Simplifying assumptions are required in order to make the modeling effort feasible. The simplifying assumptions lead to limitations in the application of the model. Simplifying assumptions are inherent in both one-dimensional and two-dimensional models.

Assumptions

Some of the assumptions required for one-dimensional modeling, however, are not required for two-dimensional modeling. The defining assumption for one-dimensional modeling is that only the forces, velocities, and variations in the streamwise direction (upstream and downstream) are significant, and that those in the transverse or lateral direction are negligible.

Two-dimensional modeling, on the other hand, is formulated to compute and account for the transverse components. Table CH12-601 below summarizes the resulting differences between two-dimensional modeling and one-dimensional modeling. Two-dimensional modeling, because it is burdened by fewer assumptions and limitations, provides advantages over one-dimensional modeling in many situations. The determination of actual conveyance and storage volume, for instance, is more accurate with two-dimensional modeling because it accounts for the ability of water to actually reach and use the conveyance or storage, instead of assuming that all available conveyance and storage is fully utilized.

Guidance to aid in deciding between one-dimensional and two-dimensional modeling in specific situations is provided later in this section. The benefits of two-dimensional modeling must be weighed against the greater effort that is often required to develop a two-dimensional model compared to a one-dimensional model. One-dimensional modeling is described in Section 1 of Chapter 10.

Geometric Input Development: One-Dimensional Modeling

The geometric input required for one-dimensional modeling is based upon the concept of a series of cross sections connected to one another along a reach. The modeler enters the sequence of the cross sections and the distance between adjacent cross sections to describe the geometric relationship between them. Any particular cross section is assumed to be oriented perpendicular to the direction of flow at all points.

The modeler can use angle points or “doglegs” in cross sections if necessary to satisfy this requirement. The cross section data can be obtained from direct survey of the cross sections, or can be derived from topographic mapping or digital terrain.

Table CH12-601. Differences between One-Dimensional and Two-Dimensional Modeling

Property or Factor	One-Dimensional Modeling	Two-Dimensional Modeling
flow direction	prescribed (streamwise)	computed
transverse velocity and momentum	neglected	computed
vertical velocity and momentum	neglected	neglected
velocity averaged over…	cross sectional area	depth at a point
transverse velocity distribution	assumed proportional to conveyance	computed
transverse variations in water surface	neglected	computed
vertical variations	neglected	neglected
unsteady flow routing	can be included	can be included

Geometric Input Development: Two-Dimensional Modeling

The development of geometric input generally requires more effort and greater availability of topographic data for two-dimensional modeling than for one-dimensional modeling. This generality does not hold true for all cases. The comparison of required effort and data for one-dimensional vs. two-dimensional model development depends on many factors, including:

- The nature and configuration of the watercourse or floodplain to be modeled
- The degree of accuracy and detail required
- The experience of the modeler in one-dimensional and two-dimensional modeling
- The availability or attainability of digital terrain model (DTM) files covering the model area
- The two-dimensional modeling program being applied

Some complex situations may be so difficult to fit into a one-dimensional framework that a two-dimensional model is actually less time consuming for model development. In such cases a two-dimensional model is likely to require much less initial deliberation and guess work than a one-dimensional model in the geometric development phase.

The geometric input required for two-dimensional modeling is a more direct representation of the terrain surface of the potential inundated area. The terrain surface can be conceptualized as a mosaic of many planar elements or tiles covering the area. The elements, depending on the program being used, may be either square cells in a regular grid, or a combination of quadrilateral and triangular elements of varying sizes. Elevations are assigned at discrete points throughout the model, usually by automated extraction from an underlying digital terrain model or DTM. The resulting terrain surface is far more detailed and descriptive than what can be accomplished with the cross sections of a one-dimensional model, but is usually much coarser than the topographic mapping or DTM from which it was derived. The geometric representation within the two-dimensional model benefits significantly from accurate and detailed topographic data. Figure CH12-601 illustrates the geometric representations for one-dimensional and two-dimensional modeling.

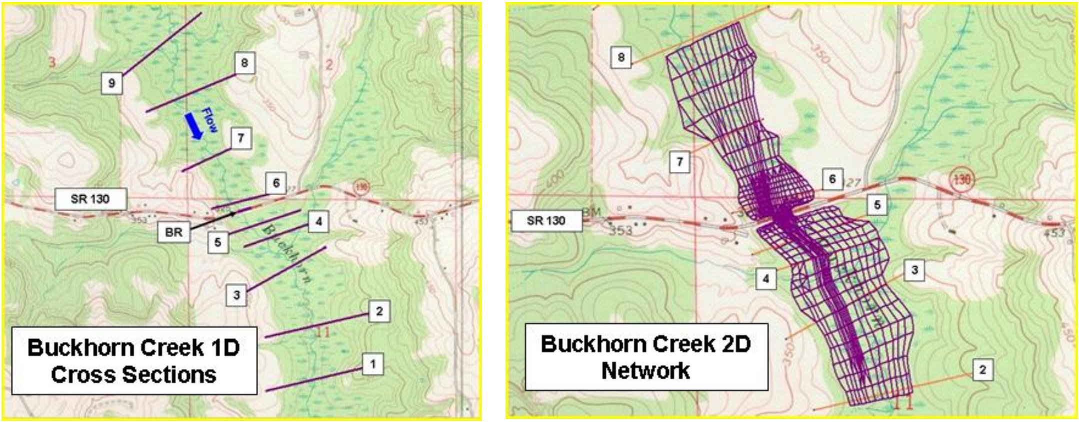

Figure CH12-601. Geometric representation for one-dimensional modeling (left) and two-dimensional modeling (right)

The development of geometric input for two-dimensional modeling is greatly aided by graphical-user-interface (GUI) software. The specific interface depends upon the modeling system being used. The most popular programs, however, all have several features in common:

- A convenient graphical environment for creating the geometric framework of the model (nodes, elements and cells)
- Tools to import background imagery (maps and aerial photographs) referenced to the desired survey coordinate system for overlaying the model geometry
- The ability to import DTM data, in one or more formats, for automated assignment of elevations to the two-dimensional model nodes or cells
- Tools to import geographic data from GIS and CADD systems
- The ability to assign hydraulic resistance parameters, such as roughness coefficients, to elements or cells one at a time or several at a time
- Easy visualization of the model input (elevation contours, perspective plotting, roughness assignments, etc.)
- User-friendly visualization of model results (inundation plots, depth contours, vectors showing velocity magnitude and direction, user-calculated variables, etc.)
- Tools to export information from model results to GIS or CADD systems

Within the GUI environment, the modeler typically starts the effort by importing geo-referenced background imagery and a DTM file. The modeler then develops the finite-difference grid or finite-element network with guidance provided by the background imagery and elevations automatically assigned from the DTM. A key decision early in the model development process is the size of the grid cells or elements. Models with smaller grid and element sizes yield more accurate and stable results, but also require more labor to develop and more computer resources and simulation time. Some two-dimensional modeling programs (of the finite-element type) allow for a variable element size, so that areas of important detail can be represented with small elements, and broad areas of low variability with large elements.

Entering Boundary Conditions and Completing Simulations

Once the geometric development is complete, two-dimensional modeling requires the modeler to specify boundary conditions just as in one-dimensional modeling. The required boundary conditions are typically: 1) the peak discharge or a discharge hydrograph at the upstream boundary of the model and 2) the water surface elevation or a stage hydrograph at the downstream boundary. With steady-flow finite-element models it is necessary to step the downstream water surface elevation from a high initial value down to its desired value through a series of preliminary simulations.

Some two-dimensional modeling projects require a significant amount of attention and troubleshooting to complete the desired model simulations. This is because the models are computationally more intensive than one-dimensional models and the numerical formulations can become unstable and diverge under some conditions. Because of the computational intensity of two-dimensional models, their use of computer resources is a factor to consider. The time required to complete a simulation is a function of the program being used, the size of the geometric network (the number of cells or elements), the number of time steps (for unsteady flow simulations), the available RAM memory of the computer, the processor speed, and in some cases the read/write speed to and from the hard drive. Running on a computer with a 2GHz processor and 1GB of RAM, a 5000-element steady-flow simulation may take less than a minute. An unsteady-flow simulation of the same model on the same computer may require several hours to run, depending on the number of time steps to be simulated.

Viewing and Using Results

Once a two-dimensional simulation has been completed, the results can be viewed in graphical, map-style format. The display of results can occur either within the GUI software that was used to develop the model or via export to a GIS or CADD system. Commonly the results are displayed as contour plots of the variables of interest, such as water surface elevation, depth and velocity magnitude. The contour plots are often overlaid with velocity vectors indicating the direction of flow (see Figure CH12-602). Modelers can also develop contour and vector plots of user-defined variables, such as shear stress, Froude number, etc. The plots of the results are often superimposed onto orthophotos and maps. The ability to create highly detailed user-friendly displays of the model results makes two-dimensional modeling a powerful tool for flood analysis and facility design, and also for communication of flood risk to stakeholders.

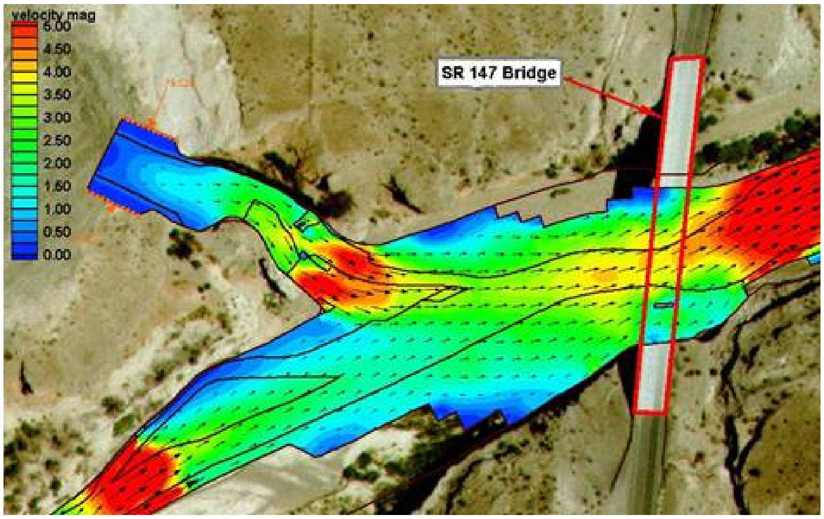

Figure CH12-602. Viewing results from a two-dimensional model

6.3 APPROPRIATE APPLICATIONS FOR TWO-DIMENSIONAL MODELING

One-dimensional modeling is adequate for most modeling needs related to floodplains and watercourses in Colorado. Occasionally, however, situations arise in which one-dimensional modeling is inadequate and two-dimensional modeling is the only viable approach. Additionally, cases sometimes arise in which one-dimensional modeling may be marginally suitable, but two-dimensional modeling offers such significant benefits that the additional effort is justified. A non-exhaustive description of appropriate applications for two-dimensional modeling follows.

Alluvial Fans

Section 1 of this chapter describes alluvial fan analysis in detail. The convex topography of alluvial fans leads to unconfined and consequently highly complex flow patterns, especially in active fan areas. Two-dimensional modeling tools have been developed that can readily analyze alluvial fan flooding, including sediment transport and debris flow/mud flow conditions. The analysis of alluvial fans with two-dimensional modeling is useful in delineating existing flood hazard areas and in evaluating design alternatives for the protection of facilities on fans. Figure CH12-603 is a plot of the results from a two-dimensional model of an alluvial fan.

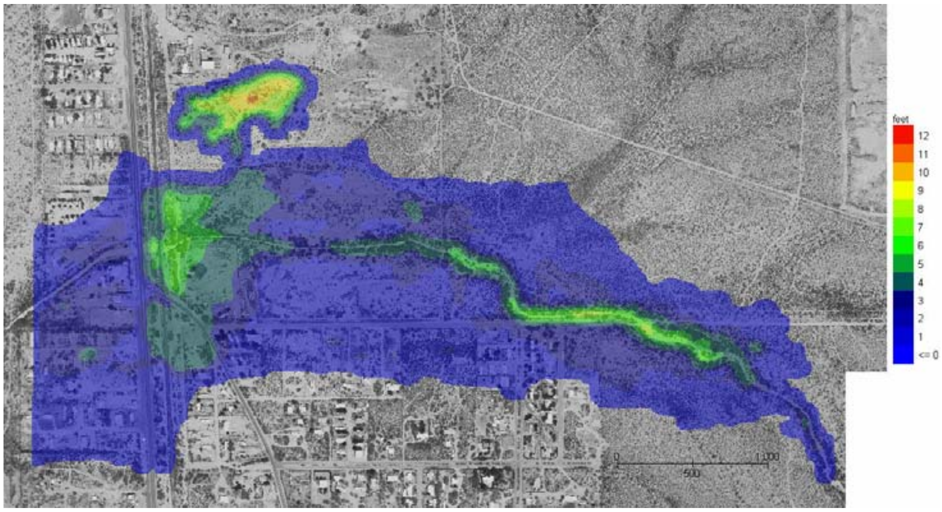

Figure CH12-603. Results from a two-dimensional model of an alluvial fan (courtesy of FLO-2D Software, Inc.)

Complex Floodplain Flow Patterns

When flooding causes a river or stream to flow out of bank, the flow patterns in the overbank areas are often highly complex. Two-dimensional modeling is often beneficial and sometimes required for accurate simulation of the overbank flow conditions. The formulation of two-dimensional models makes them well-suited for computing complex flow patterns. Some examples include:

- Flow split regions in which some or all of the overbank flow is hydraulically disconnected from the main channel flow
- Floodplains affected by sand and gravel mining with intermittent ponds and berms
- Areas where a significant portion of overbank flow is not parallel to the main channel flow (such as in Figure CH12-604)

- Floodplain areas with multiple non-continuous points of exchange between the main channel and the overbanks
- Overbanks traversed by road embankments or earth berms that are oblique to the flow direction
- Floodplain flows characterized by widespread street flooding in developed areas.
- Floodplains with highly meandering channels such that flow has to alternate between the left and right overbanks (such as in Figure CH12-605)

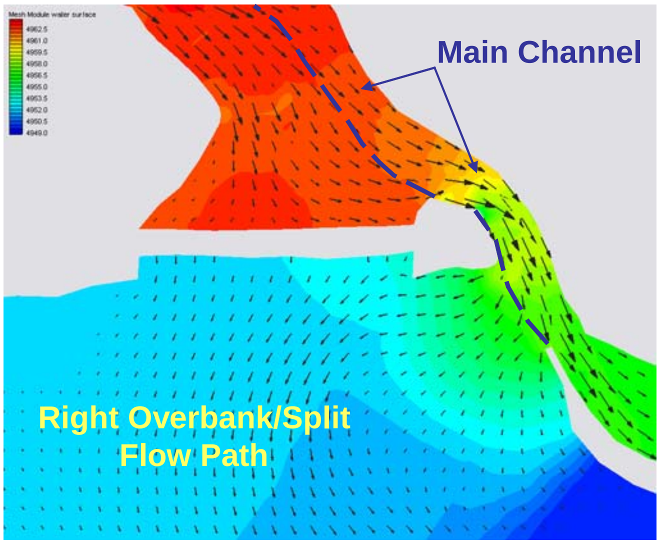

Figure CH12-604. Areas of overbank flow not parallel to main channel flow

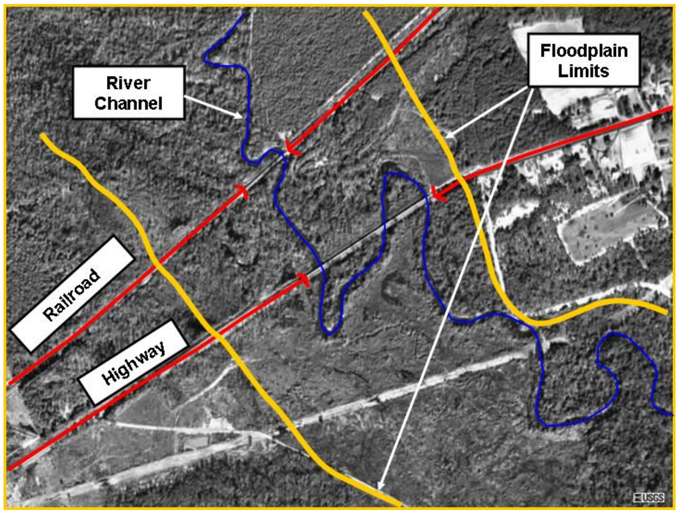

Figure CH12-605. Floodplain with highly meandering channel and parallel bridge crossings

<u>Branched or Looped Channels</u>
When the flow is divided between multiple channels, and especially when overbank flooding between the channels is occurring, the accuracy of one-dimensional modeling is significantly diminished, even if the one-dimensional split-flow capabilities are utilized. Such situations, however, are fully within the capabilities of two-dimensional models.

Complex Bridge Crossings

The hydraulics at bridge crossings can usually be analyzed with one-dimensional modeling. Some crossings, however, create such complex floodplain flow patterns that two-dimensional modeling is justified. Some examples include:

- Road embankments encroaching into the floodplain at highly skewed (non-perpendicular) angles to the flow direction
- Multiple-opening crossings (such as in Figure CH12-606)
- Crossings that cause extreme constriction, especially in wide floodplains

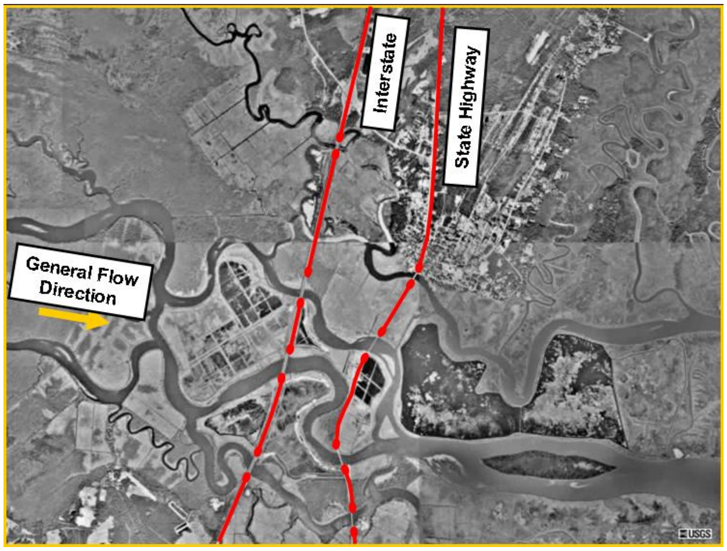

Figure CH12-606. Multiple-opening bridge crossing with branching and looped channels

Special Design Applications

Some hydraulic studies and designs depend on accurate knowledge of the hydraulic properties (velocity magnitude and direction, shear stress, depth, etc.) at one or more discrete points. Appropriately developed two-dimensional models can provide that information. Examples of such cases include:

- Design of streambank or levee protection (see Figure CH12-607)
- Scour analysis
- Stability analysis of fish habitat features (bars, spawning beds, etc.)

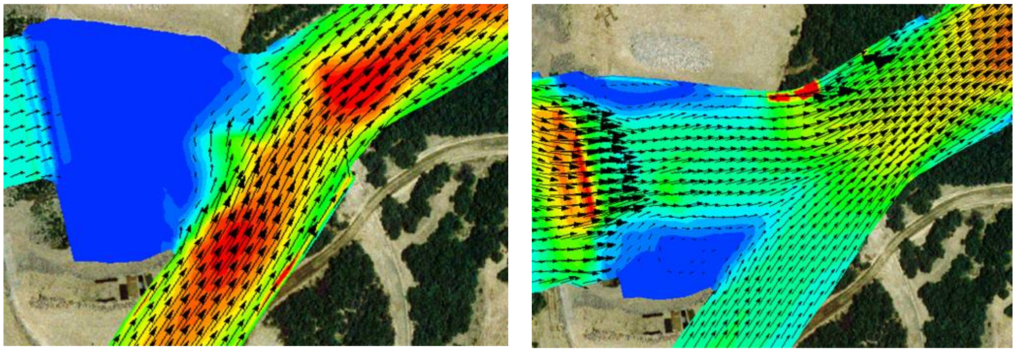

Figure CH12-607. Two-dimensional modeling results used to develop channel protection for multiple scenarios

FEMA Floodplain Studies

FEMA has approved certain two-dimensional modeling programs for use in floodplain studies, where warranted. When deciding whether to use two-dimensional modeling for a FEMA related study, certain factors should be seriously considered.

Knowledge and experience in two-dimensional modeling is much less widespread than in one-dimensional modeling. Future use and modification of the model may be limited by the technical capabilities of the engineers and floodplain managers involved.

Most available two-dimensional modeling computer programs do not have automated floodway encroachment routines. Accordingly, the establishment and verification of floodway limits must be accomplished through a trial and error process, which will typically be more time intensive than the corresponding process with a one-dimensional model.

Using two-dimensional modeling for a LOMR package may be problematic if the effective model is one-dimensional. The model limits must be selected so as to provide acceptable transitions to the existing one-dimensional models at the upstream and downstream ends. The NFIP regulations require that the program used must be available to all present and future parties impacted by the map revision. In some cases FEMA is granted a perpetual project-specific license by the software vendor. The license allows for future modification of the model by FEMA, the affected communities, or parties requesting a map revision.

Where two-dimensional modeling is justified due to floodplain complexity, a viable approach to the issues raised above is to use a two-dimensional model to guide the development of a one-dimensional model. Under this approach, the two-dimensional model is developed first, and its results provide insight as to the location and quantity of flow splits, the direction of flow for proper orientation of one-dimensional model cross sections, and the proper handling of other complex flow regions. The one-dimensional model, thus informed, becomes the effective model and is used to develop the BFE’s, floodplain delineations and floodway limits.

6.4 TWO-DIMENSIONAL MODELING TYPES AND TOOLS

Several two-dimensional modeling software programs are available. These programs typically come as modeling systems or packages that include the computational engine along with one or more graphical user interfaces for developing the input data and processing and displaying the model output. The modeling systems can be categorized into two general groups: finite-element models and finite-difference models.

Finite-element models use a numerical formulation that allows for an irregular network of elements, with wide variation in the sizes of elements. A finite-element network usually consists of a combination of quadrilateral and triangular elements. This flexibility in the geometric network makes finite element models very useful for the detailed simulation of near-field problems where vertical accelerations are not of interest, such as the hydraulics in and around stream confluences, bridge openings, hydraulic structures, bankline spurs and hardpoints, etc. Compared to finite-difference models, finite-element models are more computationally intensive, and also tend to be less stable in some situations. A particularly difficult problem in finite-element modeling is the wetting and drying of elements during the simulation. If an element starts dry but becomes inundated, or starts out inundated but becomes dry, the model often becomes unstable and diverges, rather than converging to a solution. For this reason modelers often omit shallow or fringe areas from the model domain in order to keep the modeling effort reasonable.

Finite-difference models use a numerical formulation that runs faster and is more consistently stable than finite-element modeling, but requires a uniform grid consisting of square elements throughout. Finite-difference models are much better suited than finite-element models in simulating flood wave propagation over broad, shallow floodplains. Unlike finite-element models, they can easily handle wetting and drying. These characteristics make them the best choice for modeling alluvial fan flooding, flashy shallow flooding in urban areas, and flooding of broad, flat areas due to levee breeches.

Many different two-dimensional modeling systems have been developed by federal agencies, academic institutions and the private sector. The systems accepted by FEMA on a national basis are:

- FESWMS-2DH, a public-domain finite-element model developed by the USGS in cooperation with the Federal Highway Administration (FHWA), typically used in conjunction with Surface Water Modeling System (SMS), a proprietary graphical-user interface available from Environmental Modeling Systems, Inc (EMS-I).
- RMA2, a public-domain finite-element model developed by the U.S. Army Corps of Engineers, also typically used in conjunction with SMS, a proprietary graphical-user interface available from Environmental Modeling Systems, Inc (EMS-I).
- FLO-2D, a proprietary finite-difference model available from FLO-2D Software, Inc. It is sold with dedicated pre-processing and post-processing graphical-user-interface software.
- MIKE Flood, a proprietary finite-difference model available from DHI Software. It is also sold with dedicated pre-processing and post-processing graphical-user-interface software.

FESWMS-2DH has sediment transport capability and special model features for incorporating bridge piers, pressure and overtopping flow, and culverts. RMA2 works with a related public domain program, SED2D, for sediment transport analysis. FLO-2D includes the ability to model sediment transport, mudflows and debris flows. It has been used extensively for alluvial fan modeling. Both FLO-2D and MIKE Flood have one-dimensional modeling components and other special capabilities that allow the modeler to incorporate the effects of channels, levees, bridges and other hydraulic structures into the regular grid framework.