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Flood Hazard Analysis and Mitigation

Parmeshwar L. Shrestha[1], Douglas L. Hamilton, Kristina Cydzik, Soorgul Wardak, Neil Jordan, Philip J. Shaller and Macan Doroudian

Exponent, Inc., 300 Goddard Way Suite 200, Irvine, CA 92618, USA
E-mail: [1]pshrestha@exponent.com

ABSTRACT: This paper describes the procedures adopted for delineation of flood hazards and potential mitigation measures to support the development of inland communities in California, many of which are located on alluvial fans. The streams that distribute water and sediments on the fans are not fixed in location with respect to time, but instead are subject to sudden and dramatic changes of location. Consequently, it is difficult to predict flood hazards that may impact a development located on a portion of a fan. The initial step in the assessment of the flooding potential is to examine historical flood pathways and the magnitude and timing of peak flows. The latter is dictated by the geomorphology and flood control infrastructure in the intervening lands upstream of the site. Especially critical is the determination of peak flows and hydrograph at the apex of an alluvial fan. Flood routing provides the spatial and temporal information on the floodplain inundation and peak flows impacting a site. Once the peak offsite flows have been determined, onsite mitigation measures are implemented to intercept and convey the floodwaters through and out of the site in a manner that closely mimics the natural drainage distribution. Sediment transport calculations in the floodplain and onsite channels provide a means to assess whether scour and deposition affects channel function to convey sediment through the system. A flood hazard analysis for a proposed residential development in Southern California illustrates the application of some of the methodologies and models.

INTRODUCTION

Population growth in Southern California has resulted in widespread urbanization of the inland areas. A large number of residential and commercial developments have already been constructed and many are in the planning phase. A crucial component of the planning phase is an investigation of the flood hazards associated with a proposed development and development of measures to mitigate such hazards. The objective of this paper is to describe the procedures adopted for a flood hazard study including inherent processes and potential mitigation measures to support the development of inland communities. Application of these procedures is illustrated through a case study for a proposed residential development in Southern California.

APPROACH

The flowchart shown in Figure 1 illustrates the sequence of procedures that are generally considered for a flood hazard study. These include analyses of the following components: landform, geology, historical floods, hydrology, mitigation, hydraulics, sediment transport, and flood map revision. Every project is unique, and depending on conditions in the study area, the study may include all of the aforementioned procedures or combinations, thereof.

LANDFORM ANALYSIS

Inland flood hazards are generally related to alluvial fan flooding. Because of the uncertainty in alluvial fan response to a storm event, the first step in the analysis of potential flood hazards at a site is a careful review of the landform in question. This is accomplished through field reconnaissance efforts and a study of aerial photos and topographic maps of the site and adjacent floodplain. The purpose of landform analysis is to develop an understanding of the types of hazards that exist in the study area, to identify flood sources, to ascertain alluvial fan limits relative to the limits of the site, to identify the hydrographic apex of the fan (i.e., the concentration point of the floodwater entering the fan), and to identify permanent channels at the boundaries between alluvial surfaces.

Geologic Analysis

In conjunction with landform analysis, it is important to study the geology of a site. Small alluvial fans in tectonically active regions tend to be active over a large percentage of their surfaces. Large fans located in tectonically quiescent areas or areas where climate has become more arid since the end of the Pleistocene epoch tend to have a large percentage of inactive surface area. In tectonically active areas, lateral and

[1]Conference speaker

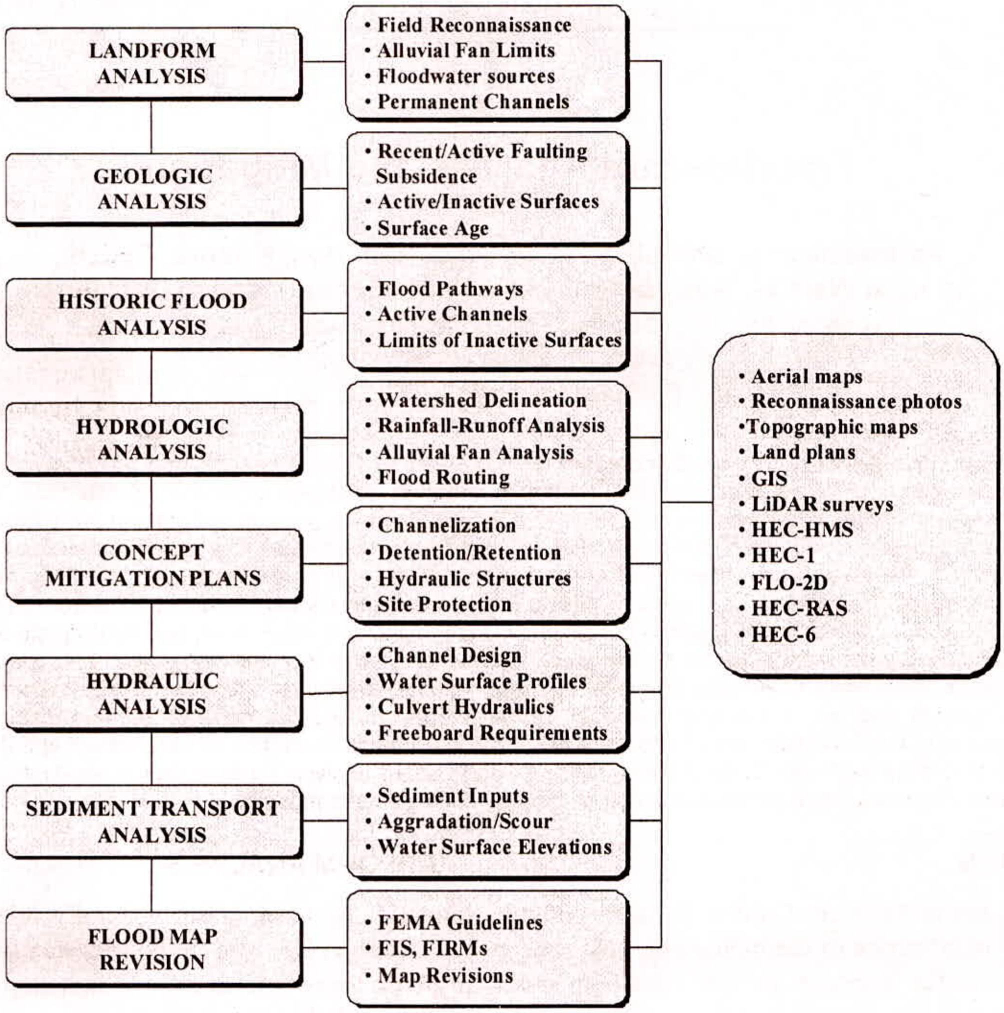

Fig. 1: Elements of flood hazard analysis and mitigation study

vertical ground movements of faults and associated landforms can result in the abandonment of alluvial surfaces and the formation of new surfaces. The purpose of the geologic investigations is to identify areas of recent and active uplift, subsidence and faulting, and active and inactive surface areas to establish the potential flood hazards at a site. Determination of the geologic age of the surfaces further serves to define the relative potential of the presence of hazards in the study area. Field inspections, available geologic maps, aerial photos, topographic maps, and Light Detection and Ranging (LiDAR) topographic imagery are utilized to develop an understanding of the geology of the site.

Historic Flood Analysis

Evidence of historic floods can be observed using the same information gathered during the geologic analysis of a site. While time erodes remnants of flood events, a wealth of information can be obtained through historical documents, particularly aerial photography. A review of historic air photos showing flood pathways provide information on the locations of recently active channels on a fan and the limits of inactive surfaces. These photos must be used with the proviso that the historic flood event might be larger or smaller than the design flood event. Also, because channels can become blocked during flood events, the same channels may not necessary be active in comparable repeated storm events. In addition, the inherent uncertainty of flood paths on alluvial fans makes it impossible to predict with certainty future flood paths. However, understanding the past responses of an alluvial fan to storm events provide clues to possible future responses.

Hydrologic Analysis

Hydrologic analysis of the study area is performed in order to estimate peak flows potentially impacting the site for storm events of various frequencies. The analysis begins with the delineation of the study area watershed, assimilation of the characteristics of the watershed such as land use, soil type, shape, slope, roughness, channel data, historical stream gage records, storm drain infrastructure, hydraulic structures, and rainfall data. Rainfall-runoff computations are carried out using hydrologic models such as the U.S. Army Corps of Engineers' (USACE) HEC-1 or HEC-HMS programs. An alluvial fan flow analysis can be carried out using the methodology developed by French *et al.* (1996) and Mifflin (undated) to estimate the portion of the alluvial fan flows from the fan apex that might reach a project site. The portion of the alluvial fan flow at the apex that has *p* percent annual chance of reaching the project site can be estimated as flow onto a line of finite length along an alluvial fan contour. The alluvial fan flow analysis calculates the flood discharge at any defined exceedence probability and is based on the inverse application of the Federal Emergency Management Agency (FEMA) FAN computer program stochastic methodology. The width over which the flows are distributed at the fan boundary can be estimated from the alluvial fan flooding flow path width equation for multiple channels developed by FEMA. A two-dimensional flood routing model (FLO-2D) can be used to investigate the propagation of floodwaters in the existing floodplain and to determine the peak discharges that are likely to cross the project site. The FLO-2D model also predicts the flow depths and velocities in the floodplain. The hydrologic analysis will also provide a means to verify flow paths identified from the geologic and historic flood analyses.

Concept Mitigation Plans

Based on the previous landform, geologic, historic floods, and hydrologic analyses, concept mitigation plans can be developed for the project site. The planned use for the site, site plans, availability of land to implement mitigation measures, and construction costs are some of the elements that need to be considered in the development of mitigation measures. Mitigation measures include provision of conveyance channels and inherent structures such as culverts and bridges, weir structures, channel stabilization methods, potential detention/retention basins, etc. The concept mitigation measures would also need to include dispersal of flows out of the project site in accordance to exiting drainage patterns. The hydrologic analysis provides estimates of the peak flows (i.e., usually the 100 year peak flows) that need to be conveyed through and out of the project site.

Hydraulic Analysis

Once concept mitigation plans have been developed, it is necessary to perform a hydraulic analysis to determine if the mitigation measures can be implemented. Computer models such as the USACE HEC-RAS model can be used to determine water surface profiles, water depths, velocities and shear stresses to assess the feasibility and performance of channels and inherent structures with respect to their ability to convey the peak flows and to ensure that sufficient freeboard is provided in the design. The hydraulic analysis would need to demonstrate that the flows exit the project site in accordance with the existing drainage patterns.

Channel stabilization and protection works can be provided based on the shear stresses induced by the flow.

Sediment Transport Analysis

A sediment transport analysis will need to follow the hydraulic analysis. Floodwaters may be laden with sediment generated in the watershed. The potential for sediment scour in the proposed channels will determine if channel stabilization measures may be necessary. Conversely, sediment aggradation in the proposed channels may decrease the conveyance capacity of the channels, thereby reducing the level of protection. Most importantly, sediment deposition might lead to an avulsion, or sudden change of flow path to an unanticipated direction. Sediment transport analysis can be performed using the USACE HEC-6 or HEC-RAS computer programs using unbulked flows to determine the extent of aggradation or scour that may occur in the system and to calculate the water surface elevations. The worst-case condition of water surface elevations resulting from either a hydraulic analysis or a sediment transport analysis is used for delineating the required freeboard. Based on the results of this analysis, further modifications to the proposed mitigation design may be necessary.

Flood Map Revision

In many cases, the subject project site may be in the flood zone, as depicted in the FEMA Flood Insurance Rate Map (FIRM). The eventual goal of performing a flood hazard and mitigation study is to demonstrate that proposed mitigation measures, if implemented, will protect the project area from the 100 year flood. To revise the existing FIRM, submittals will need to be prepared to FEMA, in accordance with their guidelines, for a Conditional Letter of Map Revision (CLOMR) followed by a Letter of Map Revision (LOMR). FEMA flood map revision adds other levels of complexity to the process. First, FEMA requires that the engineered structures on an active alluvial fan be sufficient to handle the full flow as measured at the fan apex, not the reduced flow as calculated by the alluvial fan flow analysis. Second, FEMA requires that any levees or levee-like structures (e.g., canal embankments) be certified before they can be considered to provide flood protection.

CASE STUDY

The following case study illustrates the application of some of the steps and methodologies described above for investigating the flood hazard and mitigation measures for a proposed residential development in the inland area in Southern California. The ultimate objective of the study was to revise the existing FEMA FIRM to modify the flood plain delineation for the project site. Features pertinent to our investigation include the following components: historical floods, two-dimensional flood routing, hydrology, hydraulic analysis of flood control channels, sediment transport, and FEMA FIRM revisions.

Project Location

The project site (Figure 2) is located in an existing floodplain that straddles portions of the alluvial fans derived from Thousand Palms Canyon and Pushawalla Canyon. The project area (Figure 3) is bounded on the north by Avenue 40, on the east by the Coachella Canal, on the south by Avenue 42, and on the west by Jefferson Street. The existing floodplain has historically received floodwaters originating from Thousand Palms Wash, The Indio Hills, and riverine drainage along Interstate 10. These flood flows pass through the existing Sun City Palm Desert development located about 1 mile (1.6 km) west of the project site, via three flood control channels, Channel No. 2 north of Avenue 38 at Adams Street, Channel No. 1 at Avenue 39 and Adams Street, and Channel No. 1b at Adams Street south of Avenue 39. Flood control infrastructure in the Sun City Palm Desert development, combined with the geomorphology and natural features on the intervening lands, dictate the location and timing of peak flows that would potentially impact the project site.

Historical Flood Analysis

An examination of historical flood records indicated one major flood in the Thousand Palms alluvial fan. This flood occurred on September 10, 1977. Aerial photographs taken one day after the storm indicate that floodwaters approached the project area from two locations (Figure 4). Flood paths to the south represent potential outflows from Channels No. 1 and No. 1b. The floodwaters emanate from the west crossing Jefferson south of Avenue 40. The flood paths to the north represent potential outflows from Channel No. 2. The floodwaters cross Avenue 40 at Madison Street. Some floodwater is visible on the project site flowing south along the Coachella Canal.

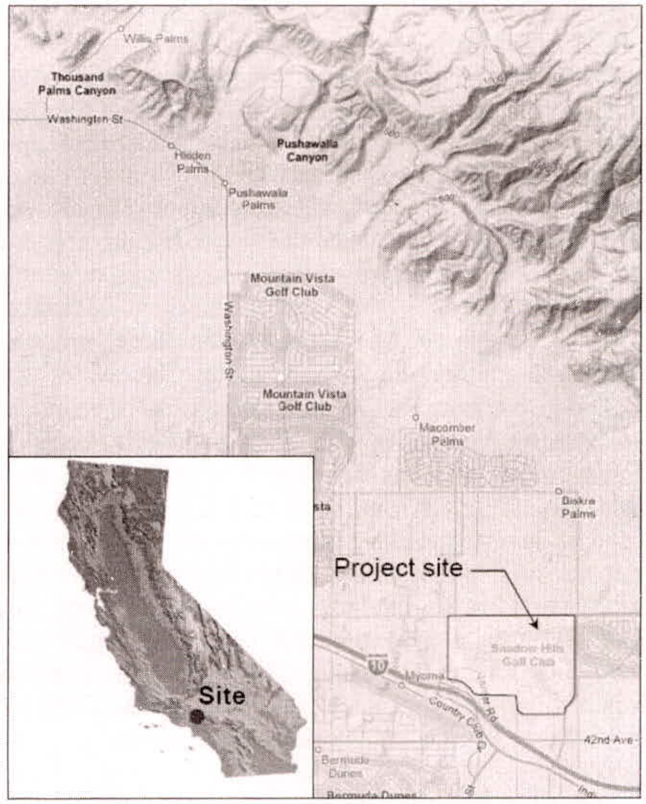

Fig. 2: Location of project area

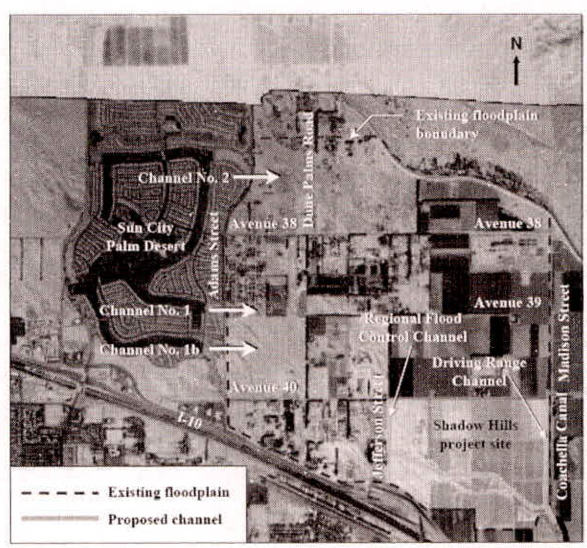

Fig. 3: Location of project area, the interim floodplain, the inflow channels No. 2, No. 1 and No. 1b, and the regional flood control and driving range channels

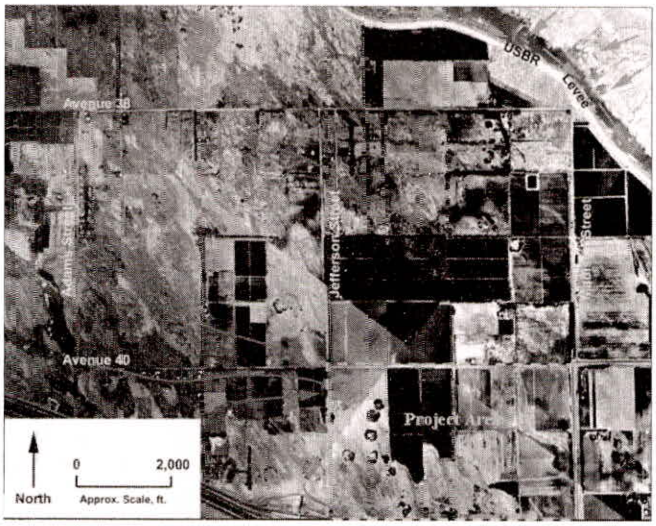

Fig. 4: Mosaic of black and white aerial photos taken one day after the major storm of September 10, 1977 (Frames 2, 3, 4, 17, 18 & 19, 9–11–77, Riverside County Flood Control)

Flood Mitigation Measures and 100 year Peak Flows

Two channels are proposed for intercepting offsite floodwaters at the historical locations identified above and conveying them through and out of the project area, as follows:

The first is a regional flood control channel (see Figure 3) designed to convey floodwaters emanating from Channels No. 1 and No. 1b. The ultimate conditions discharge (100 year peak flow) for Channel No. 1 and No. 1b combined is 31,000 cfs (878 m^3/s), which is based on the capacity of the largest flood control channel in Sun City Palm Desert. This peak flow includes the 23,000 cfs (652 m^3/s) contribution from Thousand Palms Wash and potential overflows from Morongo Wash. The hydraulic design of the regional flood control channel is based on the assumption that, in the future, there will be a continuous channel that connects the Sun City Palm Desert channels (i.e., Channels No. 2, No. 1, and No. 1b), which terminate on Adams Street, to the regional flood control channel, which starts at Jefferson Street.

The second is a flood control channel, hereinafter the driving range channel (see Figure 3), designed to convey a portion of the floodwaters emanating from Channel No. 1 and No. 1b combined or from Channel No. 2. The hydraulic design of the driving range channel was based on the peak flow crossing Avenue 40 near Madison Street which was estimated from two separate discharge conditions: (1) the ultimate conditions discharge of 31,000 cfs (878 m^3/s) for Channels No. 1 and No. 1b combined, and (2) the ultimate conditions discharge of 23,000 cfs (652 m^3/s) for Channel No. 2.

Regional Flood Control Channel

Described in this section is the development of a hydraulic model for the regional flood control channel including a sediment transport analysis for purposes of determining if the channel effectively mitigates the floodwaters through the project site.

Hydraulic Analysis

The USACE HEC-RAS computer program was used to compute the water surface profile in the regional flood control channel for a peak discharge of 31,000 cfs (878 m^3/s). The flood control channel is a "dual-use" facility serving as a golf course and a flow corridor. At the main entrance to the project site, the flow in the channel is via two concrete arch culverts 48 feet × 10 feet (14.6 m × 3 m). The main entrance would be submerged during the design flood event. For flows of 10,500 cfs (300 m^3/s) or less, all the floodwaters would pass through the culverts. For flows in excess of this amount, the additional flow would pass over the top of the road. Downstream of this section, the channel is grass-lined and is designed to have a backwater effect, which would create a submergence condition as water flows over the top of the road, which acts like a weir. Model results show maximum shear stresses along the grass-lined channel are less than or equal to 1.6 lbs/ft^2 (0.08 kPa), which are well within the maximum allowable shear stress of 3 lbs/ft^2 (0.14 kPa).

Sediment Transport Analysis

The USACE HEC-6 model was used to investigate sediment transport through the regional flood control channel. The outflow sediment transport loads for the Sun City Palm Desert channel were used as inflowing sediment loads for the regional flood control channel. This is a conservative assumption because substantial deposition of sediment is likely to occur between Adams Street and the beginning of the regional flood control channel at Jefferson Street. An unbulked peak discharge of 28,465 cfs (805 m^3/s) was used as the maximum design flood discharge. The HEC-6 model accounts for scour and deposition depths during a design flood event, and calculates the maximum water surface elevations considering a moveable bed condition. The results of our analysis show that, in general, sediment passes through the system well and is not expected to interfere with the function of the regional flood control channel. Maintenance measures will be in place in order to clean the sediment out of the channel after a large flood event.

Freeboard Requirements

The design water surface elevations in the flood control channel were based on the greater of either the HEC-RAS calculations using bulked flow or the HEC-6 computed maximum water surface elevation using the unbulked flow. All modeled sections have more than 2.5 feet (0.75 m) of freeboard between the design water surface elevation and the pad grade for the design flood event.

Driving Range Channel

Described in this section is the development of a two-dimensional flood routing model for the existing floodplain to estimate the peak flow in the driving range channel (i.e., crossing Avenue 40 near Madison Street) for two separate discharge conditions: (1) the ultimate conditions discharge of 31,000 cfs for Channels No. 1 and No. 1b combined, and (2) the ultimate conditions discharge of 23,000 cfs for Channel No. 2. Based on these peak flows, a hydraulic analysis was carried out for the driving range channel.

Two-Dimensional Flood Routing

The two-dimensional flood routing model (FLO-2D) was developed to investigate the propagation of floodwaters in the existing floodplain for purposes of determining peak flows crossing Avenue 40. There are Tamarisk tree berms that are aligned along Jefferson Street north of its intersection with Avenue 40. FLO-2D simulations were carried out without the Tamarisk berms in place. This allowed for determination of maximum discharges that are likely to cross Avenue 40 into the driving range channel. Processes simulated in the model include overland flow, infiltration and the presence of bottom roughness. The model computational domain for the floodplain area was discretized using 14,873 uniform square grids of dimension 82 ft × 82 ft (25 m × 25 m). The elevation of each grid element was based on U.S. Geological Survey (USGS) Digital Elevation Model (DEM) data, a rough grading plan for the project area, and high-resolution LiDAR survey data (Figure 5). Topographic features identified from a field reconnaissance survey were also included in the model. Figure 6 shows the topographic elevations in the interim floodplain. Floodplain areas with existing buildings, walls, berms, and trees were modeled using adjusted roughness factors. Model simulations were carried out for a period of 20 hours. Initial conditions to the model included grid elevations, floodplain storage, change in floodplain depth, average hydraulic conductivity, average capillary suction head, initial and final saturation, initial abstraction, soil porosity, and Manning's roughness coefficient.

Model results were analyzed to depict contour plots of the maximum flow depths in the interim floodplain for the two discharge conditions simulated. Inflows from Channels No. 1 and No. 1b are routed in the east and southeast directions towards Jefferson Street (Figure 7). The floodwaters cross Jefferson Street and enter the regional flood control channel in the project area. The peak discharge into the regional flood control channel was estimated to be 28,280 cfs (800 m^3/s). There is no flow contribution from this source to the driving range channel. Inflows from Channel No. 2 are routed in the east and southeast directions towards Jefferson Street and Avenue 40 (Figure 8). Some of the floodwaters cross Avenue 40 and Jefferson Street into the regional flood control channel, and some of the floodwaters cross Avenue 40 near Madison Street. The peak discharge into the regional flood control channel and the driving range channel were estimated to be about 5,250 cfs (148 m^3/s) and 7,500 cfs (213 m^3/s), respectively.

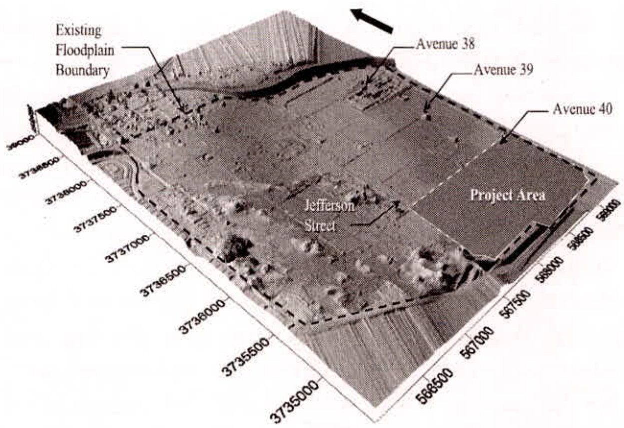

Fig. 5: Topographic features of existing floodplain and project site

Hydraulic Analysis

Based on the FLO-2D model results, a peak discharge of approximately 7,500 cfs (213 m^3/s) was estimated to enter the driving range channel across Avenue 40 near Madison Street. The HEC-RAS computer program was used to compute water surface profiles in the driving range channel. Model results show that the computed water surface elevations in the channel are below the building pad elevations specified in the rough grading plan of the project area.

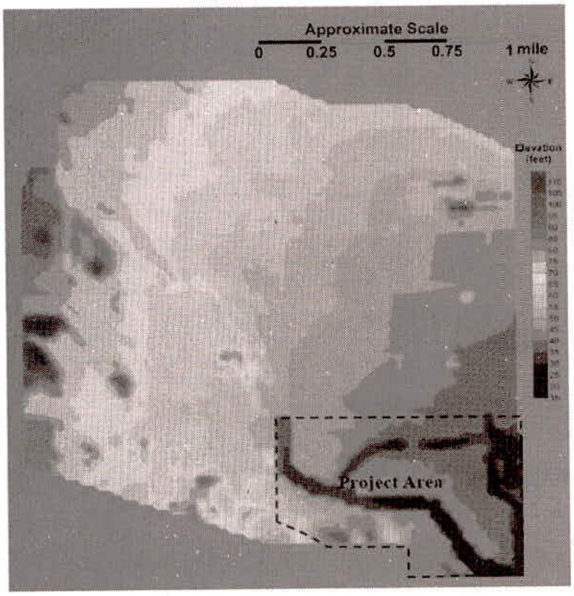

Fig. 6: Two-dimensional representation of floodplain topography

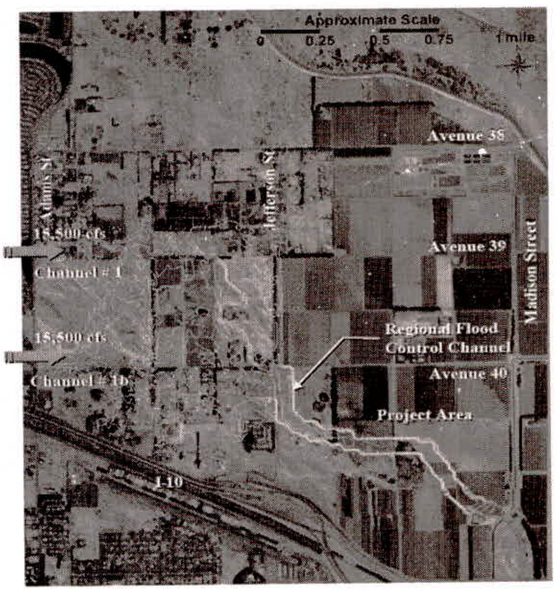

Fig. 7: Maximum water depth contours (feet) for inflows from Channels No. 1 and No. 1b

Flood Map Revision

To delineate the floodplain limits due to an effective discharge of 14,510 cfs (411 m^3/s) used in the Flood Insurance Study (FIS), the FLO-2D was simulated with an inflow discharge of 7,255 cfs (205 m^3/s) each from Channels No. 1 and No. 1b. The floodplain limits for this condition are shown in Figure 9.

The existing FIRM dated November 20, 1996 (Figure 10) shows the project area is in Zone A (i.e., areas with a 1% annual chance of flooding) for the same condition. The existing FIRM was revised to show that the regional flood control channel protects the site from the 100 year flood. The proposed FIRM is shown in Figure 11.

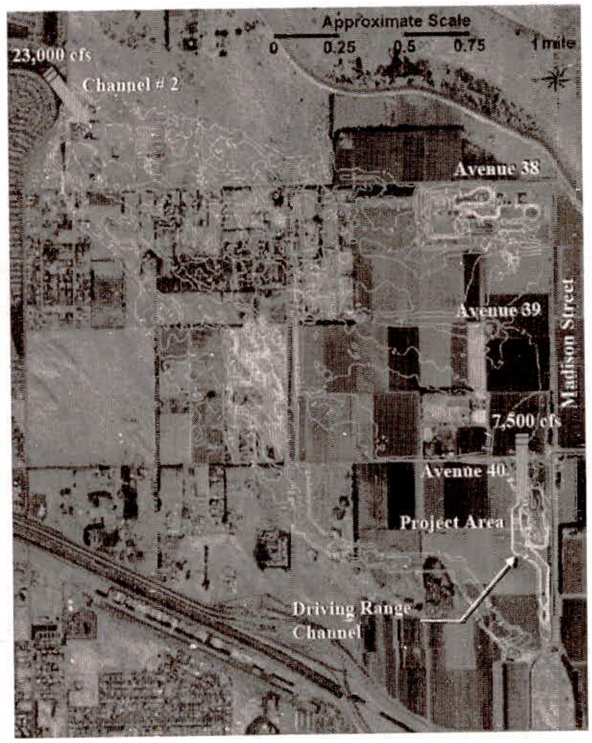

Fig. 8: Maximum water depth contours (feet) for inflows from Channel No. 2

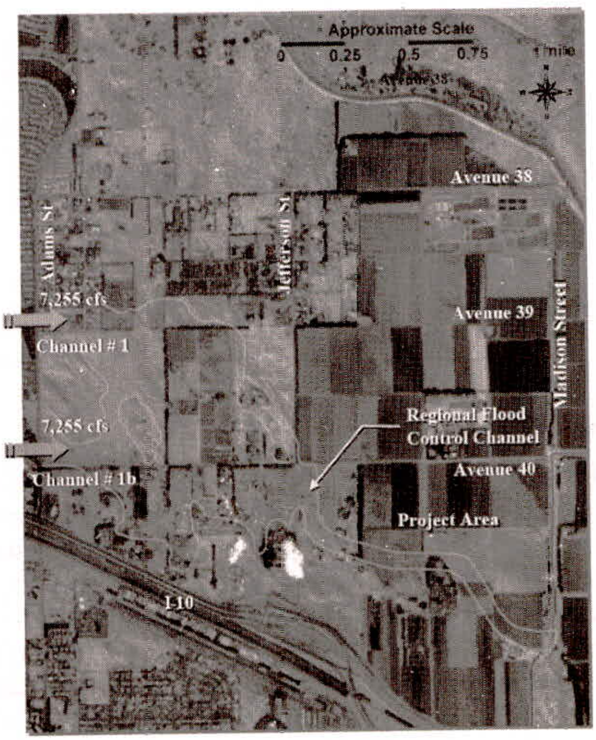

Fig. 9: Floodplain delineation using the 100-year peak flows from the flood insurance study

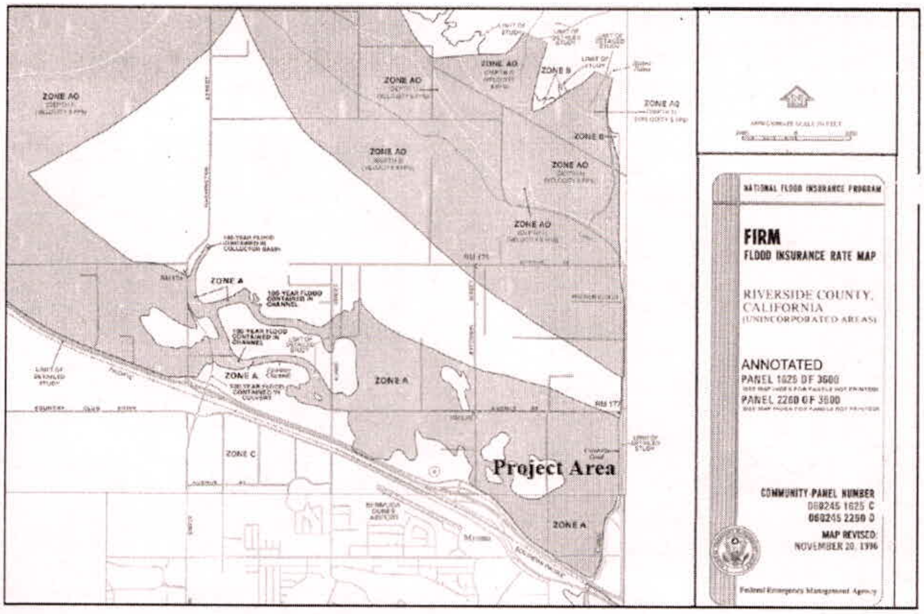

Fig. 10: Existing Flood Insurance Rate Map (FIRM)

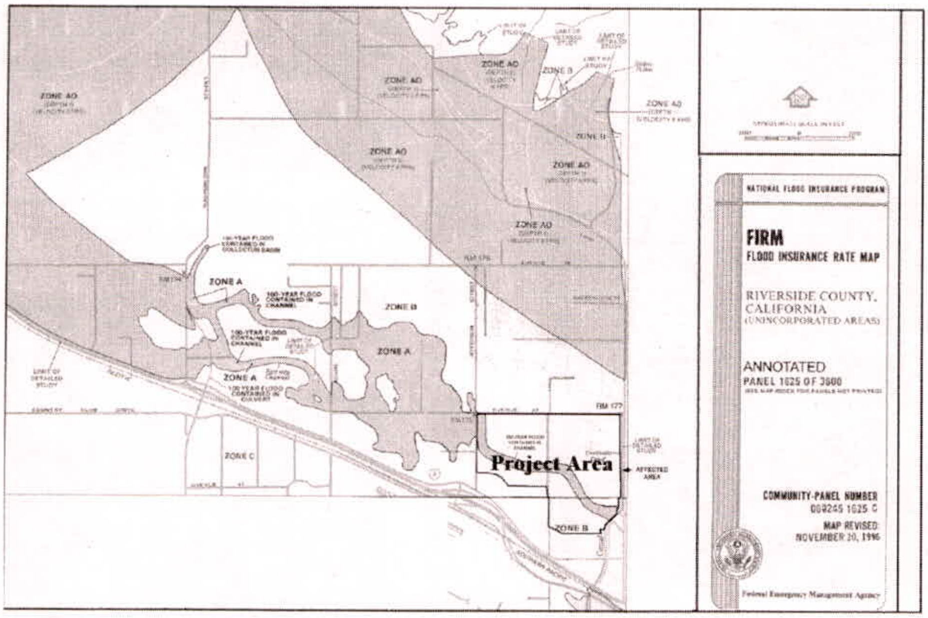

Fig. 11: Proposed Flood Insurance Rate Map (FIRM)

CONCLUSIONS

This paper describes the procedures adopted for conducting a flood hazard analysis and mitigation study to support the development of inland communities in California. Such a study involves analysis of several components such as landform, geology, historical floods, hydrology, mitigation, hydraulics, sediment transport, and flood map revision. Since each project is unique, a prototype study may involve all or some of the above components. A case study illustrates the application of some of the steps and methodologies described above. Elements of the flood hazard study include review of historic floods, development of mitigation measures, two-dimensional flood routing, hydraulic analysis of proposed channels, sediment transport analysis, and FEMA map revisions.

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