SIMULATION OF FLOOD FLOW AND SEDIMENT TRANSPORT ON ALLUVIAL FANS OF COACHELLA VALLEY, CALIFORNIA

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Abstract: A two-dimensional hydrodynamic MIKE-21 model was developed for the alluvial fan reach of the Coachella Valley between Thousand Palms and Sun City developments in South California. The model was used to simulate existing conditions flood flow dynamics and quantify the potential effect of proposed flood protection works on flooding pattern in the study area. The MIKE-21 model results were used to calculate sediment transport characteristics under existing and project conditions and to determine the project effects on sedimentation processes within and downstream of the project area. The modeling results indicate that the proposed project structures provide effective protection of Thousand Palms development against flooding and, at the same time, do not increase sediment deposition in the Sun City area.

INTRODUCTION

Flooding and sedimentation on alluvial fans are complex processes that are difficult to simulate numerically. Alluvial fans are typically characterized by irregular surface topography, complex patterns of unconfined, highly dynamic distributary flows, significant flooding and drying areas, and mixed (subcritical, critical, and supercritical) flow regimes. Alluvial fan flooding presents unique problems in terms of quantifying flood hazards, assessing sediment transport characteristics, devising reliable flood protection schemes, and evaluating impact of various projects on flow and sediment dynamics. Standard one-dimensional (1-d) methods developed for flow and sediment routing in confined streams with sufficiently simple channel geometry are usually inadequate for alluvial fan applications. For a numerical model to simulate flow and sediment transport over a fan surface, the model must account for spatial flow patterns, incorporate transient flow conditions, provide stable wetting and drying scheme, and simulate mixed flow regimes.

This paper assesses flood flow dynamics and sediment transport capacities on alluvial fans in the Coachella Valley, California and evaluates potential effects of proposed flood protection works on flow and sediment transport patterns within the project area. Flood flow dynamics was simulated using the Danish Hydraulic Institute (DHI) two-dimensional (2-d) computer model MIKE-21. Sediment transport capacities were calculated using the simulated hydraulic parameters. The sediment transport budgets were determined for both existing and project conditions, and were utilized to assess potential sedimentation impacts and maintenance requirements. The intention of the paper is to inform of the capability of MIKE-21 to simulate complex sheet flows over initially dry fan surfaces, demonstrate a method of assessing sediment transport characteristics using MIKE-21 results, and present the main simulation results of this study. All the results are presented in metric units (1 m = 3.28 ft, 1 km = 0.62 miles, 1 metric ton = 1.10 net tons).

PHYSICAL SETTINGS

The Coachella Valley is located in South California, northwest of the Salton Sea. The fluvial system of the valley consists of ephemeral stream channels (washes), which originate in the surrounding mountains and drain into large unconfined alluvial fans that spread onto the valley floor. Due to the arid environment, runoff events in the valley are infrequent and typically produced by individual high intensity storms. Long periods of several years or more may pass between significant flood events.

The study area includes approximately 12 by 12 km portion of the Coachella Valley between Thousand Palms and Sun City developments (Figure 1). The area is bordered by Indio Hills from the north and Interstate 10 from the southwest. Thousand Palms Wash, the largest Indio Hills drainage, has formed an alluvial fan more than 8 km^2 in size. The surface of the alluvial fan exhibits a network of small, shallow distributary channels that radiate from the fan apex and become indistinct a short distance downstream of the fan apex. Other streams draining the hills have much smaller watersheds and comparatively small alluvial fans. The alluvial fans are largely devoid of vegetation (Figure 2). Surface deposits primarily consist of stratified silt, sand, and gravel. The median grain sizes range from about 1 mm near the fan apexes to 0.2 mm at the base of the fans, with the area-average size of 0.58 mm (Bechtel 2002). Large dune sand deposits are frequently observed on the valley surface, caused by aeolian (wind-blown) processes that transport sand toward the southeast. The average ground surface slope ranges from about 0.025 in the vicinity of the hills to 0.005 at the valley base.

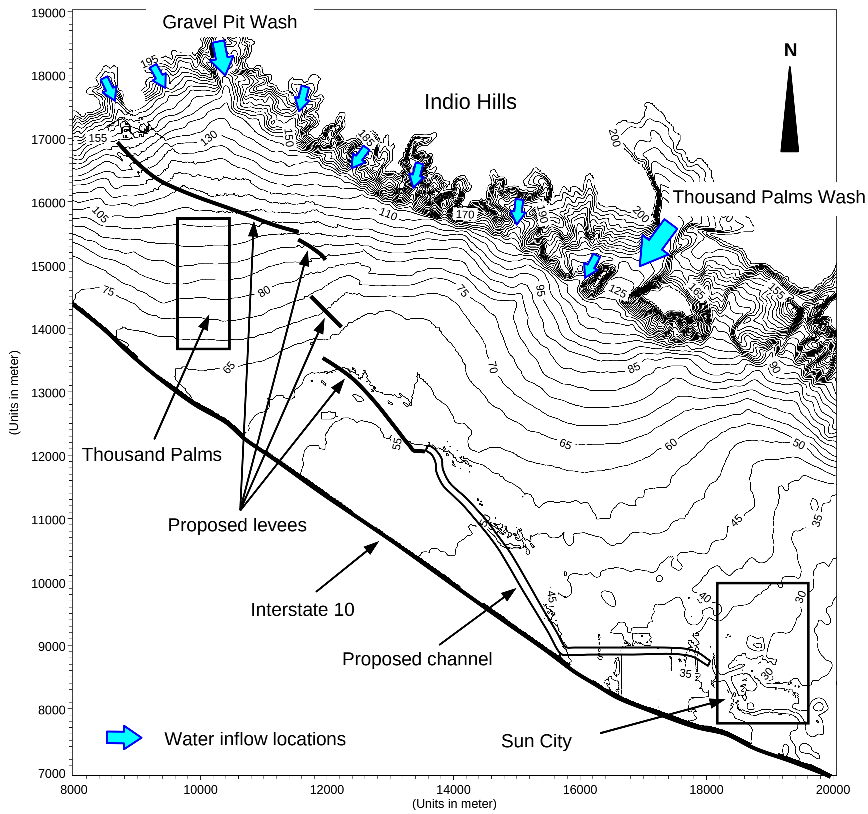


Figure 1 Study area of Coachella Valley.

Figure 2 Typical landscape of alluvial fans in Coachella Valley (left) and Sun City greenbelt channels (right).

Significant storm flows in the study area are extremely rare, typically last for a few hours, and cause widespread sheet flooding. The floodwaters emanating from Indio Hills flow in general southern direction and then southeasterly along Interstate 10. A network of floodway ("greenbelt") channels was constructed in Sun City to protect the development from flooding (Figure 2). The greenbelt channels are dry most of the time and are used for recreational purposes and as a golf course. To provide flood protection to Thousand Palms development, the U.S. Army Corps of Engineers (USACE) has designed a series of levees and a channel that would divert flows away from the developments and convey floodwaters into the Sun City greenbelt channels. The location of the proposed facilities is shown in Figure 1.

MODELING APPROACH

The modeling activities reported in this paper were aimed at the estimation of the effect of the USACE flood control project on flow conditions and sediment transport within the study area, and particularly on water levels and potential sediment deposition in the Sun City greenbelt channels. Hydrodynamic characteristics were simulated with the MIKE-21 model for the 5-, 10-, 25-, 50-, and 100-year flood events. Using the simulated flow data, sediment transport capacities were then calculated for each event. The event-based sediment transport capacities were annualized to develop an average annual sediment transport capacity. The potential impacts of the proposed flood protection project were assessed by analyzing the relative difference between the existing and project conditions flow and sediment transport characteristics.

The sediment modeling approach used in this study does not couple the hydrodynamics with the sediment transport computations. Sediment calculations were conducted for fixed bed topography, sediment was not routed between cells, and it was assumed that there was unlimited sediment supply to each cell. Therefore, the computed sediment loads represented theoretical (potential) capacity of the water flow to transport sediment, which for the sandy deposits of the Coachella Valley, however, is likely to be close to the actual sediment load.

HYDRAULIC MODELING

MIKE-21 Model: MIKE-21 is a 2-d hydrodynamic model used for computation of unsteady open-channel flows. MIKE-21 is applicable to the simulation of hydraulic phenomena in a wide range of environments including shallow sheet flows over initially dry flat surfaces. The computational procedure is based on the solution of the depth-averaged time-dependent non-linear equations of conservation of mass and momentum. The water levels and flows are resolved on a rectangular grid covering the area of interest. The main input parameters for the model are surface topography, bed resistance, location and magnitude of water inflows and outflows, initial water surface elevation, flooding and drying depths, and flow turbulence characteristic. Output parameters include water depth and 2-d water flux components at each grid point for each time step, as well as maximum inundation depths.

Model Parameters: Rectangular grids of the study area were developed for existing and project conditions using the U.S. Geological Survey 30 m Digital Elevation Model of the Coachella Valley, Light Detection and Ranging (LiDAR) data for the project area, Sun City greenbelt channel grading plans, and project structures design parameters. The model grid cell size was set to 15 by 15 m. This grid scale is sufficiently dense to describe the topographic and project features within the study area and at the same time provides manageable model run times. To eliminate any effects of the model boundaries on the solution in the study area, the downstream model limit was extended approximately 16 km below Sun City. The Manning roughness coefficient for the study area was set to 0.05 in accordance with the earlier study of Simons, Li and Associates (2000). Nine isolated time-variant flow sources were specified at the fan apexes to simulate model inflows and a set of sinks was specified at the downstream model extent to remove water mass from the model. Inflow hydrographs were developed by the USACE and employed in the MIKE-21 model. Comparison of the inflow hydrographs for the 100-year flood event is shown in Figure 3. The initial water surface elevation was set at ground level (i.e. the initial bed surface was dry). The simulation time step was set to 3 s to maintain computational stability (Courant numbers less than one) for velocities less than 5 m/s. Flooding and drying depths (0.02 and 0.01 m, respectively), as well as eddy viscosity (1.5 m^2/s) were developed using procedures recommended by DHI. Infiltration water losses were not simulated due to the absence of relevant calibration data. Model results were stored at 10-minute increments to provide sufficient resolution of the output hydrodynamic data. The simulation period was 24 hrs and included the major phase of the simulated flood events.

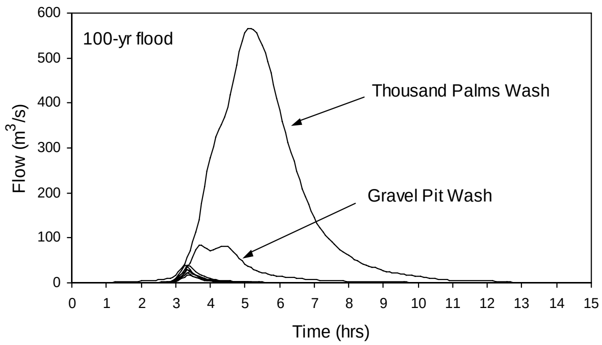


Figure 3 Inflow hydrographs for 100-year flood event.

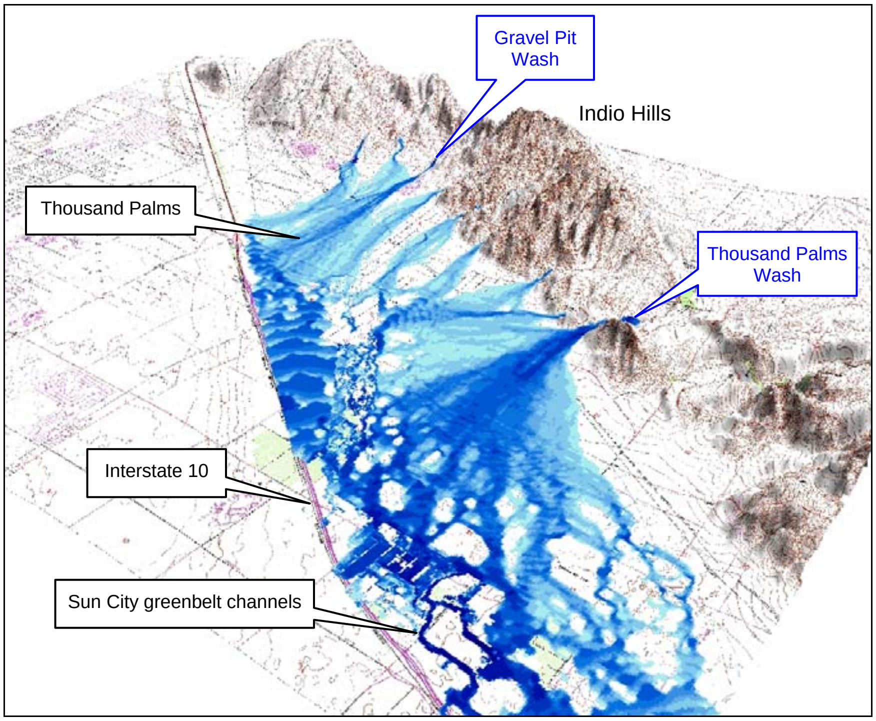
Existing Conditions Flood Simulations: Under existing conditions, floodwaters spread over vast expanses of the valley between Indio Hills and Interstate 10 (Figure 4). Thousand Palms Wash provides the largest flow magnitude and volume to the study area and inundates larger areas than the other smaller tributaries. The flows from Thousand Palms Wash moving in southern direction comprise the first and the largest flood wave reaching the Sun City area. Floodwaters from the four westerly most drainages flow southward through Thousand Palms development toward Interstate 10 and then continue southeasterly along Interstate 10. Storm flows from the other drainages head in general southeasterly direction towards Sun City. The inundation depths are generally less than 0.5 m for Thousand Palms Wash and Gravel Pit Wash and less than 0.2 m for the other drainages. For higher flood events, the inundation area tends to increase, but the flows remain relatively shallow. Comparison of the inundation limits simulated for the 100-year flood event with aerial photographs of the Thousand Palms September 11, 1977 flood (shown in Figure 5) indicates that the model is capable of simulating complex sheet flows and closely replicates the observed flooding pattern in the study area.

Project Conditions Flood Simulations: Under project conditions, flows emanating from Indio Hills are effectively intercepted by the levees and redirected across the fan surfaces and through the project channel to the Sun City floodway channels (Figure 4). The project provides effective protection of Thousand Palms development, reduces inundation area, and at the same time reduces travel time and attenuation of the flood wave and increases the peak flows delivered to the Sun City greenbelt channels. The peak flow in the greenbelt channels increases under project conditions from about 1 to 20 m^3/s for the 5-year flood event and from 260 to 400 m^3/s for the 100-year event, which results in 0.2-0.6 m increase of maximum water depths Flooding pattern in the northeast part of the study area is not affected by the project structures.

SEDIMENT CAPACITY MODELING

Sediment Transport Calculations: The hydraulic data computed by the MIKE-21 model were used to calculate time-variant sediment fluxes and cumulative event-based sediment volumes (yields) at each grid cell of the computational domain. The calculations were performed for each flow scenario using the Ackers and White (1973) total sediment load function. A single sediment size of 0.58 mm, corresponding to the mean grain size in the project area was used in the calculations. A computer program was written to perform the sediment transport calculations. This program reads hydrodynamic data from the MIKE-21 output file, computes hydraulic parameters, performs sediment transport computations, and creates output data file that can be visualized and analyzed using the MIKE-21 viewing tools.

Existing Conditions Sediment Transport Capacities: The modeling results indicate that sediment transport generally follows water flow patterns, is highly non-uniform, and occurs over large expanses of the alluvial fans (Figure 6). Thousand Palms Wash has the highest sediment transport capacity and is potentially by far the most important contributor of sediment to the project area. Total sediment transport capacity of Thousand Palms Wash at the fan apex ranges from about 200 tons for the 5-year flood to 59000 tons for the 100-year flood, the long-term average annual being 1900 tons. The flow downstream of Thousand Palms Wash outlet spreads over the much flatter valley, which results in the reduction of the flow sediment transport capacity. The calculated sediment delivery to distal fan region near Sun City is less than 12% of sediment transport capacity at the fan apex. Due to their high magnitude, the flows from Thousand Palms Wash are responsible for the most of sediment transport in the vicinity of and through the Sun City greenbelt channels. Sediment contribution from the other sources is appreciably smaller.



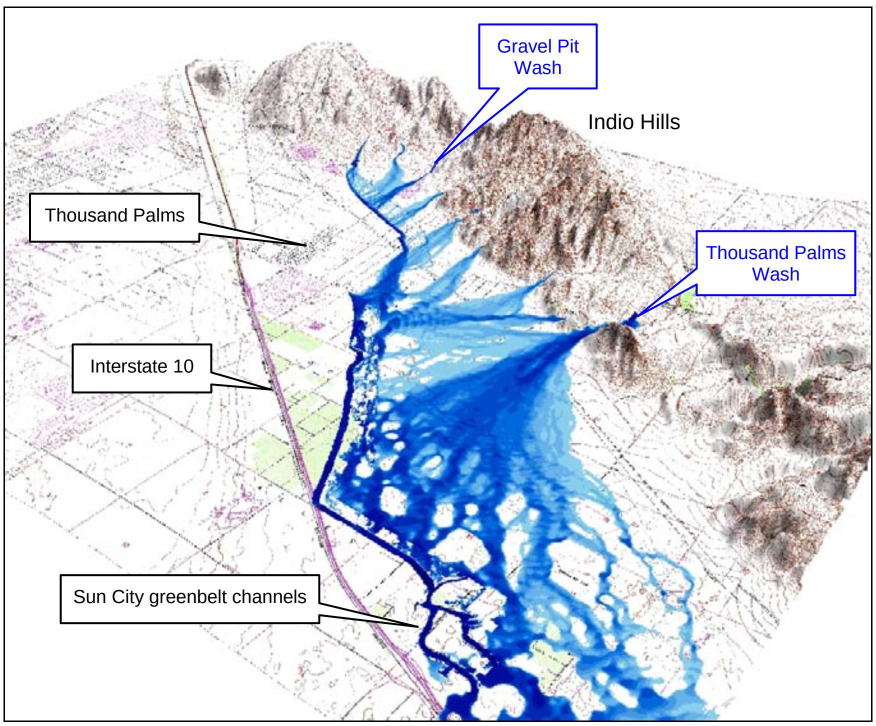


Figure 4 Perspective views of inundation limits simulated for 100-year flood event under existing (top) and project (bottom) conditions. Darker areas indicate deeper flows. Vertical exaggeration = 5.

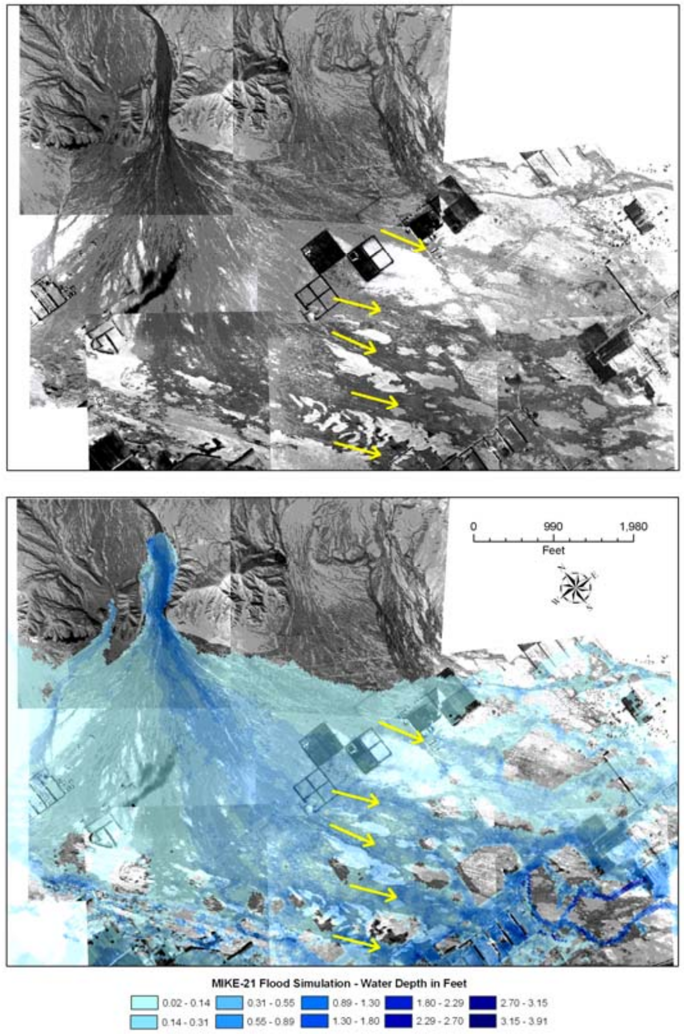


Figure 5 Comparison of simulated 100-year flood inundation limits with September 11, 1977 Thousand Palms flood aerial photographs. According to Exponent (2002), this flood has exceeded the 100-year event. Arrows delineate significant flow paths common to both model results and aerial photographs.

The calculated potential sediment inflow to the greenbelt site ranges from 15 tons for the 5-year flood to 7300 tons for the 100-year floods, the average annual being 172 tons (Table 1). At the same time, capacity of the greenbelt channels is estimated for the same floods at about 1 and 570 tons, respectively, with the average annual capacity of only 12 tons. Thus, under existing conditions, sediment transport capacity of the greenbelt channels is less than 10% of potential sediment inflow. The Sun City greenbelts serve as sinks for inflowing sediment and during floods they will intercept the majority of the sediment supplied to the Sun City area. The amount of sediment that can potentially deposit in the greenbelt channels varies from 14 tons for the 5-year flood event to about 6730 tons for the 100-year event. The long-term, statistically averaged annual deposition in the Sun City greenbelts is estimated at about 160 tons.

Project Conditions Sediment Transport Capacities: The proposed flood control project significantly alters sediment transport patterns in the western and southern parts of the project area and does not affect sediment transport in the northeast portion of the valley. Sediment transport activity is concentrated in a narrow band along the project levees and in the project channel (Figure 6). Sediment transported by Thousand Palms Wash comprise the first sediment input to the Sun City greenbelt area, which is shortly followed by additional concentrated sediment inputs from the other streams originating from Indio Hills.

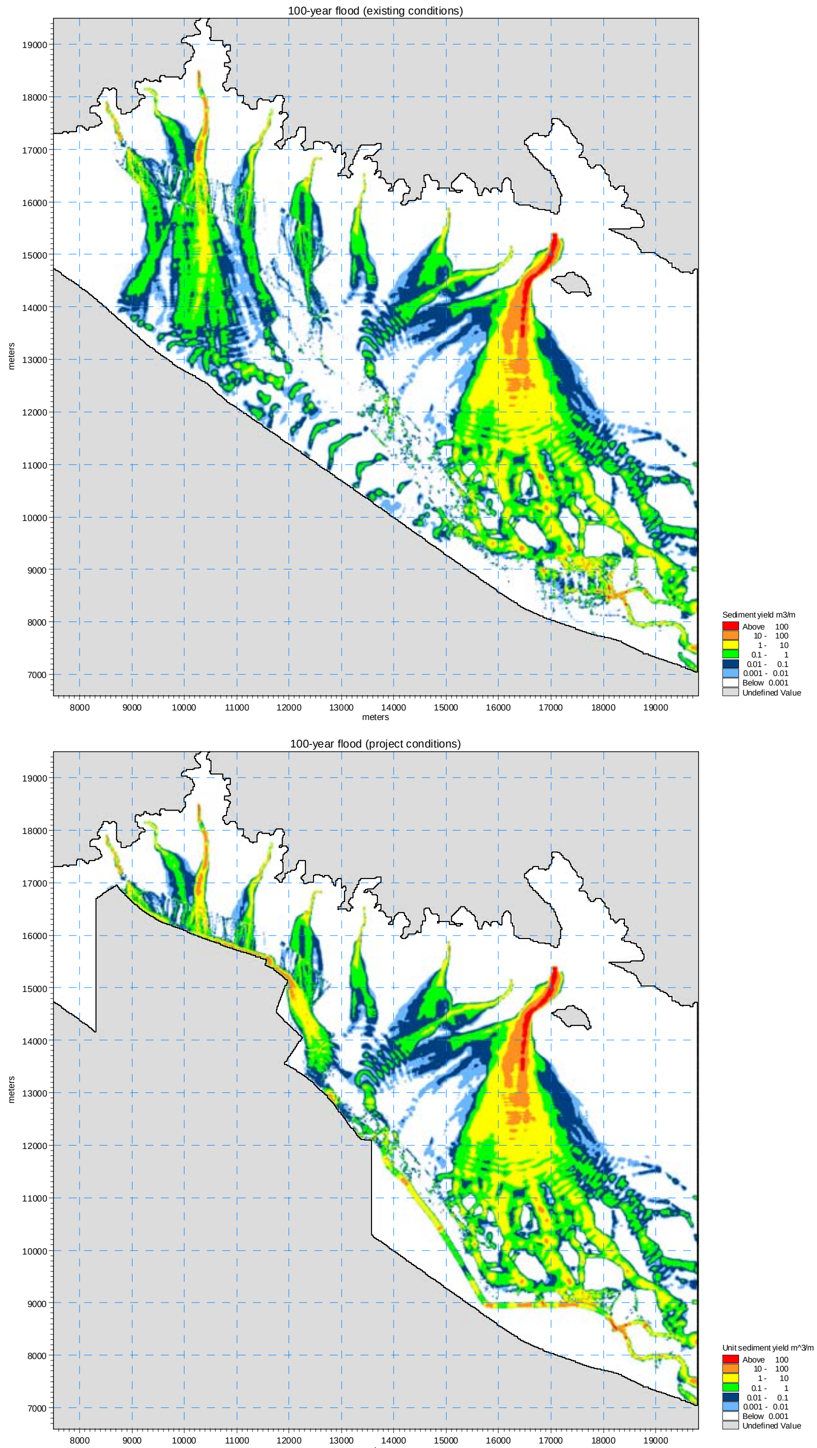


Figure 6 Sediment yields calculated for 100-year flood event under existing (top) and project (bottom) conditions.

The calculated sediment inflow to the greenbelt area varies under project conditions from 16 tons for the 5-year flood to 4700 tons for the 100-year flood, with the average annual sediment inflow of 145 tons (Table 1). Project conditions sediment transport capacity of the greenbelt channels ranges from about 4 tons for the 5-year flood to 1500 tons for the 100-year flood event, the average annual being 34 tons. The potential sediment deposition in the greenbelt channels ranges from 12 tons for the 5-year flood to 3200 tons for the 100-year flood, with the long-term average annual deposition of 111 tons. Comparison of the existing and project conditions results indicates that that the project has varying effect on event-based sediment loads in the Sun City greenbelt area (see Table 1). The long-term effect, however, is a 16% reduction of the sediment inflow to the greenbelt area, 180% increase of sediment transport capacity of the greenbelt channels, and 30% reduction of potential sediment deposition in the greenbelt channels. The calculated sediment loads do not include infiltration water losses and, therefore, the sediment assessment results presented here should be regarded as conservative estimates.

Table 1 Sediment transport capacities and potential deposition calculated for Sun City greenbelt area.

Flood event	Existing conditions			Project conditions		
	Inflow to greenbelts (tons)	Capacity of greenbelts (tons)	Potential deposition (tons)	Inflow to greenbelts (tons)	Capacity of greenbelts (tons)	Potential deposition (tons)
100-year	7300	570	6730	4700	1500	3200
50-year	1800	150	1650	2000	420	1580
25-year	560	16	544	860	69	791
10-year	90	3	87	91	19	72
5-year	15	1	14	16	4	12
Average annual	172	12	160	145	34	111

Comparison of Fluvial and Aeolian Sediment Yields: High winds blowing in the Coachella Valley in the southeastern direction convey appreciable amounts of sand from the fan aprons towards Sun City. Estimated rates of aeolian sediment transport in the study area range from about 4 to 37 tons/m/year (Weaver 1979). Sun City development extends approximately 800 m across the wind corridor, which gives annual aeolian sediment supply into the Sun City area in the range of 3000 to 30000 tons. This amount is one to two orders of magnitude larger than the calculated average annual fluvial sediment supply to the greenbelt channels. Thus, sediment transport in the study reach of the Coachella Valley is dominated by aeolian processes.

CONCLUSIONS

The results of this study indicate that the proposed flood control project effectively intercepts and redirects floodwaters emanating from Indio Hills and provides effective protection of Thousand Palms development. At the same time, the project reduces travel time of the flood flows from the northwest part of the project area, which increases the peak flows and maximum water depths in the greenbelt channels. Sediment transport is concentrated in a narrow band along the project structures, which generally reduces the potential long-term average annual sediment inflow to and deposition in the greenbelt channels under project conditions. Flooding and sediment transport patterns in the northeast part of the study area are not affected by the project. The calculated fluvial sediment loads in the Sun City area are insignificant compared to the amount of sediment transported by aeolian processes.

ACKNOWLEDGEMENTS

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