

Simulation of Rio Grande Floodplain Inundation Using FLO-2D

J. S. O'Brien
W. T. Fullerton

Abstract—Spring floodplain inundation is important to the natural functions of the Rio Grande bosque biological community including cottonwood tree germination and recruitment. To predict floodplain inundation, a two-dimensional flood routing model FLO-2D will be applied to various reaches of the Rio Grande. FLO-2D will assess overbank flooding in terms of the area of inundation, floodplain hydraulics and river discharge timing, frequency and duration. Floodwave attenuation is important in predicting floodplain inundation. Initial FLO-2D applications will be made to the Isleta reach (15 miles) south of Albuquerque and to a 20 mile reach near the Bosque del Apache Wildlife Refuge.

The Rio Grande Bosque Hydrology Group has identified several important projects designed to improve the natural functions of the Rio Grande bosque biological community. One of these projects is to investigate the potential for overbank flooding to support cottonwood tree germination. To predict overbank flooding discharge, the FLO-2D model will be applied to various reaches of the Rio Grande downstream of Cochiti Reservoir. The initial test application of the model was made to a 15 mile reach of the Rio Grande downstream of the Isleta Diversion Dam south of Albuquerque. The second FLO-2D application will be made to a 20 mile river reach near the Bosque del Apache National Wildlife Refuge. FLO-2D will assist in analyzing overbank flooding in terms of timing, frequency and flood duration.

The prediction of overbank flooding and the application of the FLO-2D model is a joint cooperative study involving the support of the Albuquerque Projects Office of the Bureau of Reclamation, the Fish and Wildlife Service and the Army Corps of Engineers. All three agencies have been involved in several aspects of this project including floodplain mapping, river channel morphology and application of the model. The Fish and Wildlife Service has supported the Bosque floodplain mapping and the initial test application of the FLO-2D to the Isleta reach. The Isleta reach cross section survey was conducted through a joint funding effort of the Fish and Wildlife Service and the Corps of Engineers. The Corps of Engineers have performed the digital floodplain mapping used in the both the Isleta and Bosque reaches and supported the initial applications of the model. Primary funding support for Bosque del Apache Wildlife Refuge project and for the floodplain mapping was provided by the Bureau of Reclamation. The Bureau was also responsible for getting

the cross section surveys completed. All three agencies have purchased or obtained a copy of the FLO-2D model for future applications.

FLO Engineering, Inc. is an engineering contractor for the Bureau of Reclamation specializing in hydrographic data collection, river channel morphology and hydraulic engineering. Hundreds of cross sections throughout the Middle Rio Grande valley have been surveyed by FLO Engineering, Inc. The hydrographic data base compiled by the Bureau on the Middle Rio Grande includes aerial photography, ortho-photographic mapping, discharge measurements, sediment transport and bed material data and numerous cross section and floodplain surveys. These data constitute one of the best hydrographic data bases on any river in the country. From this data base, the FLO-2D model input data files will be developed.

Description of the FLO-2D Model

FLO-2D is a commercially available proprietary model created by FLO Engineering. It has been applied to numerous flood hazard simulation projects throughout the west including routing Green River seasonal flows from Flaming Gorge to the Colorado River confluence and numerous alluvial fan flood hazard delineation projects. FLO-2D is a two-dimensional, finite difference flood routing model using either a kinematic wave, diffusive wave or the full dynamic wave version of the momentum equation for unconfined, overland flow or channel flow. It simulates the progression of the flood hydrograph, conserving flow volume, over a system of square grid elements representing topography and flow roughness. FLO-2D is an ideal model for river channel overbank flooding, alluvial fan flows, flow through urban areas, or the hydraulic design of flood mitigation measures. The model has a number of components which can enhance the detail of a flood simulation including channel-floodplain discharge exchange, loss of storage due to buildings, flow obstruction, rill and gully flow, street flow, bridge and culvert flow, levee and levee failure, mud and debris flow, sediment transport, rainfall and infiltration (fig. 1). FLO-2D has been used by federal and state agencies and numerous consulting firms.

Creating a FLO-2D data base

A FLO-2D project data base requires a representation of the potential flow surface topography in a square grid format. A simple procedure has been devised with CADD software for generating the grid system. Most CADD systems contain survey routines which enable a grid system to be overlaid on a digitized map and the coordinates and elevations exported to a file. Any size grid element can be used by the model, but the timestep is governed by the wave

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J. S. O'Brien and W. T. Fullerton are Hydraulic Engineers, FLO Engineering, Inc. Breckenridge, CO.

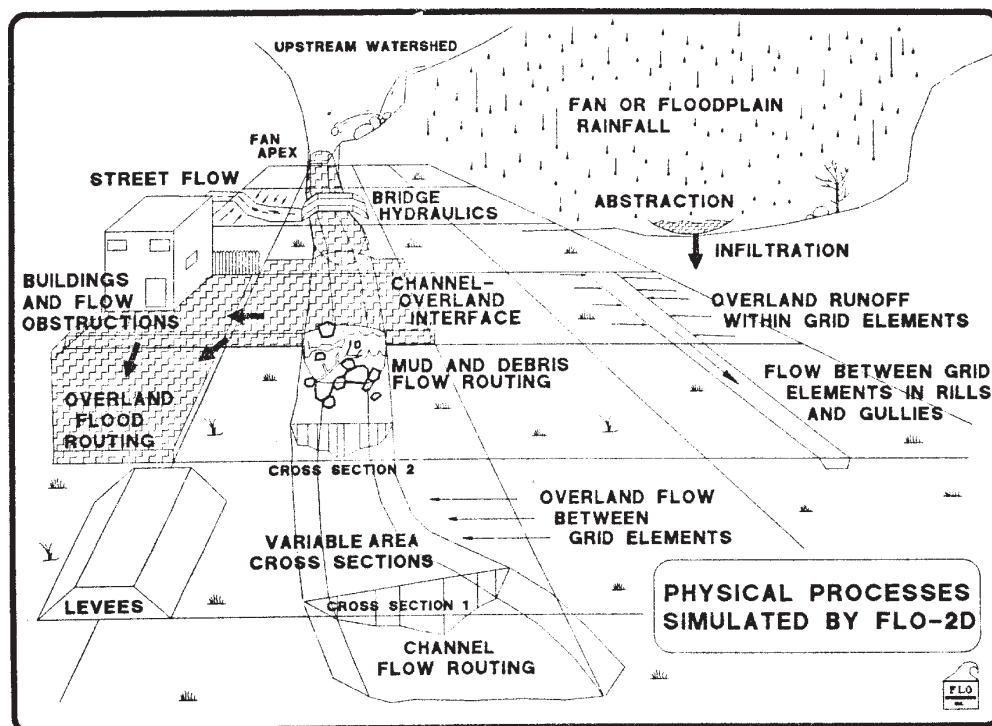


Figure 1—Physical Processes Simulated by FLO-2D.

celerity and very small grid elements will require very small timesteps. A typical grid element is 200 ft to 500 ft, but grid elements ranging from 50 ft to 2,000 ft have been used in simulations. The number of grid elements is essentially unlimited.

Routing Algorithm Stability and Volume Conservation

The timestep is incremented or decremented according to strict flood routing numerical stability criteria. Numerical stability has been linked to volume conservation which is the basis for the model accuracy. When the model accurately conserves volume, the model runs faster. If the model is gaining or losing volume, the timesteps decrease. Volume conservation is carefully tracked and is reported both during the simulation and in output files. Typically timesteps range from 1 to 60 seconds.

Overland and Channel Flow - Exchange of Channel and Floodplain Discharge

Overland flow is simulated in eight directions (4 compass and 4 diagonal directions). One-dimensional channel flow is simulated with rectangular, trapezoidal or natural shaped cross sections. A preprocessor program will convert HEC-2 cross sections into a data file formatted for FLO-2D. The channel width can be larger than the grid element allowing for more detailed floodplain simulations. When the flow in the channel exceeds the bank height, FLO-2D will compute the overbank discharge. This channel-floodplain flow interaction can occur with overland return flow to the channel

(fig. 2). This is an important component for the application of the model to the Rio Grande. The number of inflow tributaries is unlimited.

Overland flow can be concentrated in small rills and gullies as multiple channel flow. When specific grid elements are assigned multiple channels, discharge between those elements occurs as concentrated flow in small, rectangular channels and not as overland sheet flow. Rainfall on the overland portion of each grid element is routed into the element rill or gully. More than one gully can be specified for a grid element. When the rill or gully depth is exceeded, the channel is expanded by a preassigned incremental width to contain the gully flow. Variable rill and gully channel characteristics can be spatially delineated on the grid system.

Mud and Debris Flows

Hyperconcentrated sediment flow is simulated using viscosity and yield stress relationships as function of sediment concentration. Several such relationships have been analyzed in the laboratory representing different soil types and conditions. Very viscous mudflows may cease flowing on very rough surfaces or very mild slopes. Conversely, mudflows can be diluted by rainfall inflow. Storage in small debris basins and spillway discharge can be simulated.

Sediment Transport—Aggradation and Degradation

Sediment transport is computed for arid region alluvial systems using the Zeller-Fullerton equation. Almost any sediment transport relationship can be programmed into the model. For the Rio Grande bosque project, three new

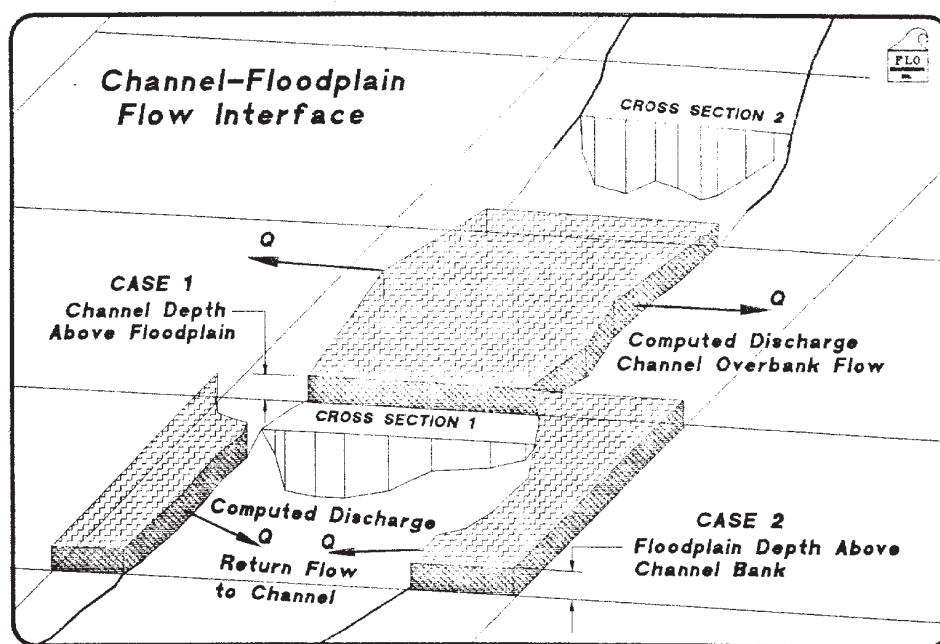


Figure 2—Channel-Floodplain Flow Interface.

sediment transport equations will be added to the model. Aggradation and degradation is predicted if the sediment transport routine is invoked. Scour and deposition are distributed uniformly on the grid element surface or channel bed.

Other FLO-2D Components

Rainfall and infiltration can be simulated on the potential flow surface before or during the flood simulation. The rainfall is then routed as overland sheet flow or as rill and gully flow until it intercepts a main channel. Infiltration is simulated with the Green-Ampt infiltration model and can be spatially variable on the flow surface.

Street discharge is simulated as flow in a shallow rectangular channel. Streets may intersect and are delineated with a width and curb height. Bridge and culvert flow on the grid system can be simulated by user specified relationships between the discharge and headwater depth.

Levees can be simulated by specifying flow directions and crest elevations. Levee failure can occur by overtopping or at a prescribed levee stage for a specified time period. Levee failure is simulated on a grid element by grid element basis.

Flow around buildings and obstructions and floodplain storage loss due to structures can be simulated on a grid element basis. A portion or the entire grid element can be removed from potential inundation. Similarly, the flow transfer between grid elements can be partially or entirely obstructed.

FLO-2D Results

Spatially and temporally varied output including flow depth, velocity, discharge hydrograph, sediment concentration and

bed elevation are written to output files. Discharge hydrographs can be established for any channel or any overland grid element in the system. Outflow grid elements can be reviewed separately. Grid elements can be grouped together as cross sections to generate flow hydrographs. Maximum depth, velocity and discharge files are automatically created. The flood progression over the flow surface can be viewed graphically along with a plot of the inflow hydrograph while the model is running. The most common desired result is a map of the maximum flow depths depicting the maximum area of inundation.

Application of FLO-2D to the Rio Grande Isleta Reach

In 1997, the Bosque Hydrology Group reviewed the potential application of the FLO-2D model to predict overbank flooding along the Middle Rio Grande. Through funding support from the Bosque Initiative and in cooperation with the Corps of Engineers Albuquerque District, the FLO-2D model was applied to a 15 mile reach of the Rio Grande downstream of the Isleta Diversion located south of Albuquerque. This reach was identified by the Corps of Engineers as a potential restoration area where overbank flooding may enhance the bosque biology.

The Corps developed a digital terrain map (DTM) and overlaid a grid system of 8,024 elements, 500 ft square (fig. 3). The river reach included 234 channel elements represented by 11 surveyed cross sections and 9 cross sections extracted from the 1995 DTM mapping. Infiltration and the levee system were modeled. Three flood hydrographs were simulated: The 250-year project flood event with a peak discharge of 42,000 cfs; the 100-year flood with a peak

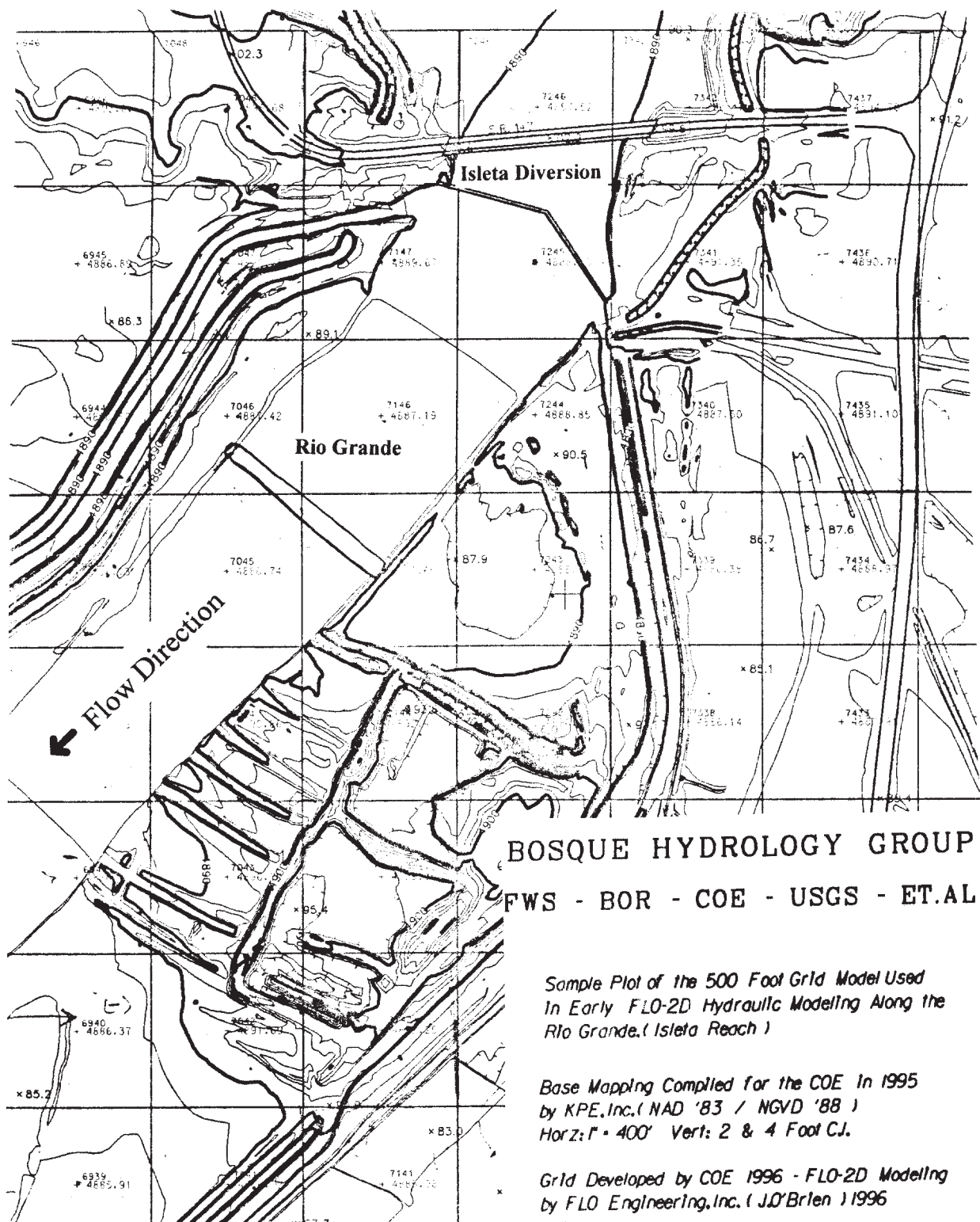


Figure 3—FLO-2D Grid System at the Isleta Diversion, Rio Grande

discharge of 15,326 cfs; and a high flow season hydrograph with a peak discharge of 7,000 cfs. The project flood event was simulated as both a levee and no-levee scenario. The spatial flood inundation results are viewed graphically when running FLO-2D or the post-processor programs.

Although this was a simple test application to determine the utility of the model for predicting overbank flooding on the Rio Grande, the results proved to be interesting. The Corps of Engineers had originally modeled this reach with HEC-2, a single discharge, one-dimensional step-backwater hydraulic model. The project flood event results essentially indicated bluff to bluff flood inundation across the Rio Grande valley for the 40,000 cfs peak discharge. FLO-2D routed the entire hydrograph and it was revealed that because the hydrograph volume was so limited, floodwave attenuation through the reach was pronounced and much of the overbank flooding was abated by the end of the reach. In the levee flood scenario, levees were overtopped in the upstream 30 percent of the reach inundating about 40 percent of the floodplain outside the levees. In the downstream half of the reach, all the overbank flooding was confined between the levees. No bluff to bluff flooding was predicted with the FLO-2D model.

Without the levees, the flood inundated approximately 50 percent of the floodplain in the reach. Most of the floodplain inundation occurred in the upstream half of the reach. Again, the floodwave attenuation was so pronounced that only a small portion of the reach was flooded. Higher floodplain depths were predicted along the eastern edge of the floodplain against the valley bluff. The results from these flood scenarios indicate that the flood hydrograph had a very limited volume. The peak discharge decreased from 40,000 cfs at the start of the reach to a predicted 25,700 cfs at the end of the reach for the levee simulation and to a predicted 15,700 cfs for the no-levee simulation. The importance of overbank flooding in floodwave attenuation is clearly demonstrated in this test. The levees increase the potential downstream flooding. If this Isleta reach is similar to the upstream reach for several miles, it is unlikely that the 40,000 cfs peak discharge would arrive at the Isleta Diversion without experiencing some attenuation.

The 100-yr flood was only simulated for the case with the levees. All of the overbank flooding was contained between the levees. A portion of the channel in the lower third of the reach conveyed all the flow. There was no predicted overbank flooding for a reach of approximately two miles. The 100-yr hydrograph peak discharge did not significantly attenuate.

The final flood simulation involved the high flow seasonal discharge related to spring runoff of 7,000 cfs. In this flood scenario, the areas of floodplain inundation were of primary interest. Most of the upstream half of the reach was inundated, but only about one-third of the downstream half of the reach was flooded. Channel conveyance capacity was greater in the lower portion of the river reach. There was no significant floodwave attenuation.

The test application of FLO-2D to the Isleta reach proved successful in several aspects. First, it was ascertained that the model could successfully identify which reaches might be preferable for overbank flooding. Secondly, the test demonstrated the importance of routing the flood hydrograph. Timing and flow duration will be critical to assess overbank

flood potential in reaches further downstream of Isleta. Given a prescribed volume as a flow augmentation release from Cochiti Dam to enhance overbank flooding, the release hydrograph can be adjusted to maximize either flood duration or area of inundation in various reaches. Finally, the FLO-2D simulation highlighted several drawbacks in the existing Isleta Reach data base.

Accurate prediction of floodplain inundation along the Rio Grande is contingent on three important factors; adequate DTM mapping (both in topographic accuracy and contour resolution), appropriate cross section spacing and calibrated roughness parameters. Through the FLO-2D Isleta application, it was determined that the eleven surveyed Cochiti cross section lines provided by the Bureau and recently re-surveyed by FLO Engineering did not match the extracted DTM cross sections developed by the Corps of Engineers. The two sets of cross sections were out of phase (they weren't surveyed in the same season) and Corps cross sections did not represent a complete picture of the channel (thalwegs were estimated). As a result, when the Isleta reach model was developed, some grid elements had adverse bed slope conditions and inappropriate roughness Manning's n-values. Cross section and n-value adjustments were made to permit the model testing to proceed, but it became apparent that additional data collection was necessary to upgrade the Isleta reach data base to obtain reliable results. Specifically, the following hydrographic data collection will be required:

- Additional cross sections are needed in transitional reaches where the channel changes from a narrow to a wide cross section.
- All the cross sections should be surveyed in a relative short period of time during a period of high flows to avoid the effects of scour and fill in a reach.
- Water surface elevations should be surveyed at all the cross sections during a relatively short period in conjunction with a discharge measurement to calibrate the n-values during high flow.

It is anticipated that these data will be collected during this spring runoff to enable the Isleta Reach to be accurately modeled with FLO-2D to predict potential overbank flooding.

Prediction of Flow Hydrographs Using FLO-2D

The National Park Service and the Fish and Wildlife Service Denver Office supported the development of a FLO-2D discharge routing model for the Green River in Utah from Flaming Gorge Dam to the confluence of the Colorado River, a distance of 412 miles. The FLO-2D model was proposed as hydrograph routing tool to support flow recommendations for the Flaming Gorge biological opinion being written by the Fish and Wildlife Service. To develop the routing model, a digital topographic map was prepared, all available Green River cross section surveys were compiled and inflow hydrographs were assembled. This included seasonal high flow hydrographs of Flaming Gorge Dam releases and the tributary inflow of the Yampa, Duchesne, White, Price, and San Rafael Rivers as well as Brush and Ashley Creeks.

The project goal was to use FLO-2D to predict the seasonal flow hydrograph at any location in the Green River downstream of Flaming Gorge Dam on a daily basis. The project objectives included:

- Calibration of the model for the 1996 high flow season.
- A review of the model accuracy by simulating the 1997 high flow data.
- An estimate of floodplain inundation area for these two flow years.
- Simulation of the Flaming Gorge jet tube releases.
- Prediction of discharge timing and duration at any location in the Green River.

Green River flows were simulated for 100 days of the 1996 high flow season beginning on April 1 and ending on July 9. In 1996, five level loggers for monitoring river stage were established throughout the Green River system. Combined with the USGS gages at Jensen and Green River, they constitute a system of seven known discharge points with which to calibrate the FLO-2D predicted hydrograph.

A 2,000 foot square grid system was overlaid on the digitized base map resulting in 2,482 grid elements of which 962 were designated as channel elements. A total of 268 surveyed cross sections were analyzed for channel geometry relationships and assigned to the channel elements. Channel roughness and infiltration parameters were adjusted within acceptable ranges to calibrate the predicted hydrograph at the seven points of known discharge in the Green River. Generally, the final Manning's n-value ranged from 0.024 to 0.050 with the higher n-values assigned to grid elements in the steep canyon reaches. Some channel element cross sections and roughness values were adjusted to reduce the abrupt transition between grid elements. The assigned cross sections created adverse slope conditions for some elements in the channel profile. For these elements, the channel depth and bed elevations were adjusted to achieve a uniform reach slope.

FLO-2D predicted a hydrograph for every channel grid element (every 2,000 ft) throughout the Green River system from Flaming Gorge to the Colorado River confluence. The 1996 measured hydrographs were used to calibrate the model and then FLO-2D was applied to 1997 flows using the same channel data base. Excellent correlation was achieved between the FLO-2D predicted hydrograph and measured discharge hydrograph at the USGS Jensen gage located at one-third of modeled river system (fig. 4 and 5). Further downstream at the USGS Green River gage (about two-thirds through the system), there was some disparity between the predicted and measured discharge hydrographs (fig. 6 and 7). The differences between the predicted and measured hydrographs were attributed to:

- Small unmeasured tributary inflow between Jensen and Green River.
- Storm inflow reflected in spikes in the measured discharge.
- Canal diversion at Green River, Utah.
- Estimated discharge reported for the Green River gage (discharge record errors).
- Variable infiltration and evaporation losses in the reach from Jensen to Green River.

Despite these correlative discrepancies, the USGS Green River gage data compared very favorably with the FLO-2D predictions.

The utility of the FLO-2D model was further demonstrated by simulating flows without the storage effects of Flaming Gorge reservoir and by adjusting Flaming Gorge Dam releases. These simulations indicated a substantial increase in floodplain inundation when Flaming Gorge releases were timed to occur with the peak discharge in the Yampa River. This application of FLO-2D to the Green River illustrated the flexibility of the model as a management tool.

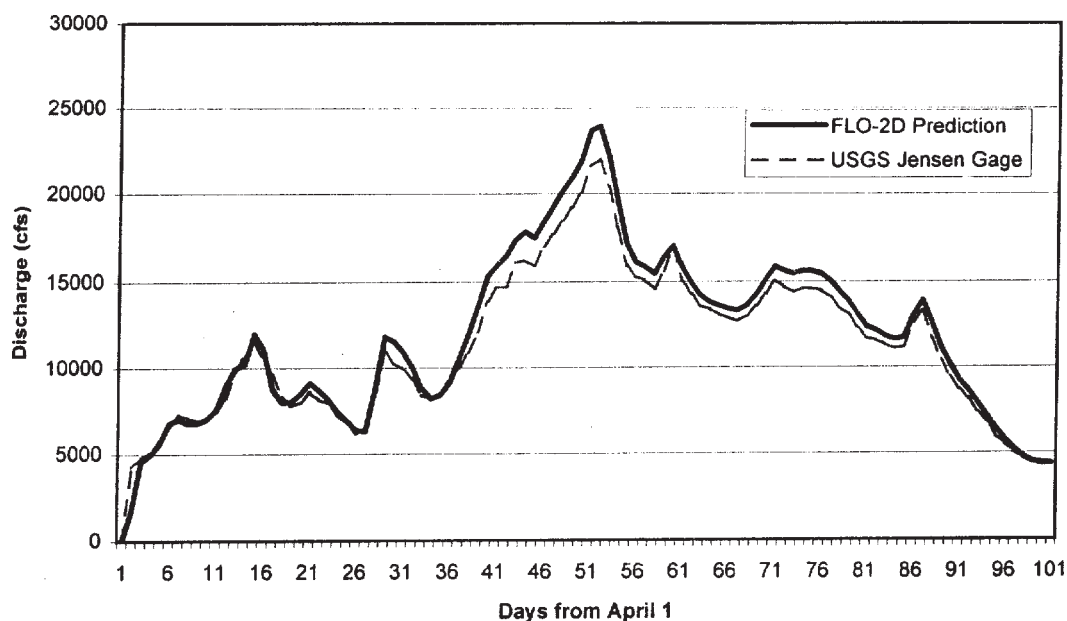


Figure 4—1996 Green River Hydrograph at Jensen, Utah

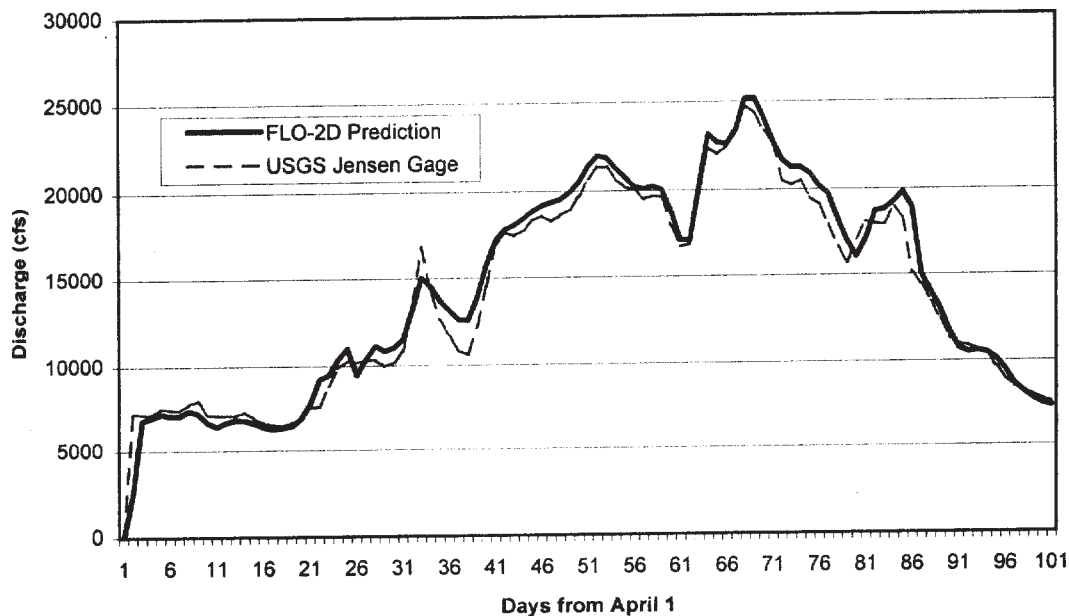


Figure 5—1997 Green River Hydrograph at Jensen, Utah

Application of the FLO-2D

Through the cooperation of the Albuquerque Projects Office of the Bureau of Reclamation, Corps of Engineers, and the Fish and Wildlife Service, the FLO-2D model will be applied to a 20 mile reach of the Rio Grande near the Bosque del Apache National Wildlife Refuge south of San Antonio, New Mexico. The modeled reach will extend from the Highway 380 bridge to the south boundary of the refuge. This project will encompass several aspects of the Rio Grande

hydrology and channel morphology. The goal of the project is to design a seasonal high flow hydrograph that will inundate selected areas of the floodplain in this reach. The high flow hydrograph will be analyzed in terms of its frequency and flow duration. Initially, FLO-2D will be used to simulate flow with a rigid boundary model. In subsequent applications, FLO-2D will simulate channel flow with a mobile bed. Several sediment transport models will be tested and calibrated.

Preparation of the FLO-2D data base for Bosque reach began last year when a series of 41 cross sections were

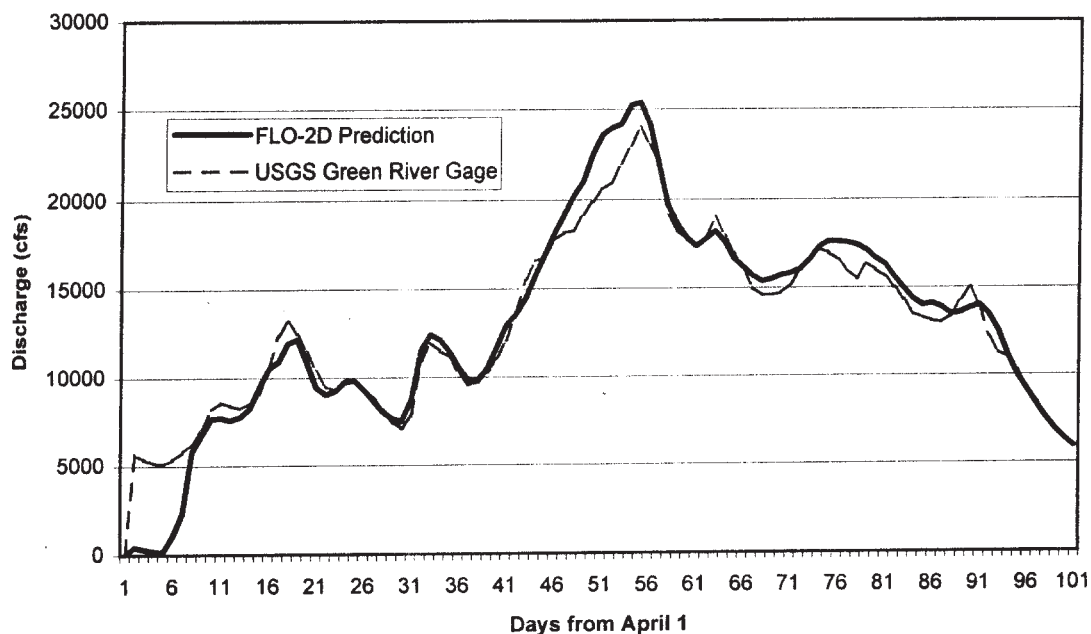


Figure 6—1996 Green River Hydrograph at Green River, Utah

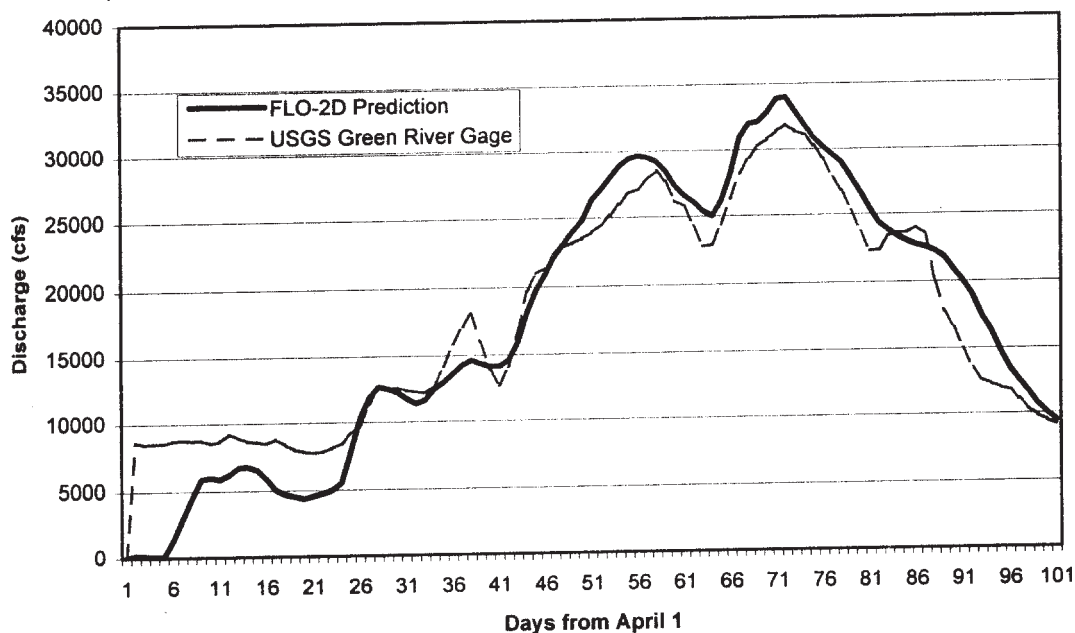


Figure 7—1997 Green River Hydrograph at Green River, Utah

surveyed in the study reach. The majority of these cross sections have been surveyed several times over the last decade. Twelve new cross sections were established in transition reaches from a narrow to a wide channel. A digital map of the floodplain with 2 foot contours has been completed from aerial photogrammetry by the Corps. On this base map, a 500 ft square grid element system will be overlaid for the FLO-2D model. The base map can be used by all researchers participating in the Bosque Initiative. In addition, water discharge, sediment load, bed material sizes, water surface elevations, aerial photos of overbank flooding and other hydrographic data have been collected over the past several years which will be applied to calibrate the model. Three flow hydrographs will be simulated:

- 10-year average hydrograph (peak discharge ~ 4,500 cfs)
- 2-year return period hydrograph (peak discharge ~ 8,470 cfs)
- Low flow period hydrograph (peak discharge ~ 3,500 cfs)

An important part of this project will be the model calibration to existing data bases. In several locations along this reach, bed scour reduces the propensity for overbank flooding during high flows. At 3,000 cfs, the water surface in certain locations may be within a half foot of being bankfull. Later in the hydrograph at a flow of 5,000 cfs, the water surface elevation may be foot below the top-of-bank. This channel bed response is difficult to predict because it depends on sediment supply as well as flow hydraulics. The Bureau has developed a total load rating curve which will be applied as the sediment supply to the study reach. One project objective will be to determine the importance of channel bed response to high flows in terms of the area of inundation. Generally, the volume of the water stored in the channel at a given time is relatively minor compared to the total volume in the flood hydrograph, however, changes in

channel cross section and conveyance can significantly impact the location at which overbank flow occurs. For this reason, both a rigid bed and mobile bed analysis will be conducted with the FLO-2D model. At least three sediment transport equations will be used in the model calibration.

It is anticipated that the model data base will be developed during this summer and the project will be completed by the end of 1998. The final product of this flood routing project will be an area of floodplain inundation versus discharge relationship that might be incorporated into reservoir operation and Rio Grande flow management to promote overbank flooding near the Bosque del Apache National Wildlife Refuge. The FLO-2D results and projected flood inundation maps combined with projections of the Rio Grande hydrology can be the basis for decisions regarding frequency, duration and timing of high flows. This project objective is a focal point of the proposed Rio Grande bosque restoration. If the FLO-2D simulations are successful, there is interest in developing the FLO-2D model for the entire Middle Rio Grande from Cochiti Dam to Elephant Butte Reservoir.

Conclusions

The FLO-2D model will be used to investigate the potential for limited overbank flooding along various reaches of the Middle Rio Grande to enhance the natural functions of the bosque biological community and to increase opportunities for cottonwood tree germination. Overbank flooding will be evaluated in terms of river discharge, timing, frequency and duration. The model has demonstrated its utility on the Isleta reach illustrating the importance of simulating floodwave attenuation. In an application for the Green River in Utah, the FLO-2D model accurately replicated season hydrographs measured in various locations throughout the

river system. In the coming year, the Isleta reach simulation will be finalized and the model will be applied to a 20 mile reach of the Rio Grande near the Bosque del Apache National Wildlife Refuge. The results of the model will include area of inundation versus discharge/duration relationships which can be used to investigate various combinations of reservoir releases and operations.

Acknowledgments

The application of the FLO-2D model to the Middle Rio Grande is a cooperative effort of the Fish and Wildlife

Service, Bureau of Reclamation and Corps of Engineers. The primary participants in this effort include Paul Tashjian and Jeff Whitney of the Fish and Wildlife Service, Drew Baird of the Bureau of Reclamation, and Doug Wolf and William DeRagon of the Corps of Engineers. Support for this project came from all three agencies with the Bureau of Reclamation being the primary source of funding. The Bosque Initiative provided the initial impetus to examine the potential for applying the FLO-2D model to the Isleta Reach. The Bosque Hydrology Group of the Bosque Initiative is central forum for discussion, direction and review of the FLO-2D simulations.