Two-Dimensional Flow Analysis Report for the Lee Moore Wash Basin Management Study in Pima County Arizona

Prepared for and in cooperation with the
Pima County Regional Flood Control District

While under contract and in cooperation with
Stantec Consulting Inc.

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Expires 3/31/2012

December 2008

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Pima County Contract Number 16-59-S-138098-0606, Change Order 1

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Abstract

A two-dimensional analysis of rainfall runoff from within the distributary flow areas of the Lee Moore Wash Basin was conducted using the FLO-2D flood routing model (FLO-2D FRM). Direct runoff was computed with the FLO-2D FRM via the SCS Curve Number (CN) Procedure. The CN procedure was incorporated into the FLO-2D FRM by the writers of the FLO-2D program specifically for this project following Pima County Regional Flood Control District methodology for computing runoff. FLO-2D models were calibrated to HEC-HMS models by varying input and modeling parameters including grid size, roughness coefficients, and roughness adjustment equation options. The 100-year, 3-hour and 24-hour storms were modeled and indicate approximately 50% of the study area is impacted by 100-year flooding. The two-dimensional modeling predicted a 100-year peak discharge of over 20,000 cfs within the Lee Moore Wash channel where it crosses the Union Pacific Railroad Bridge. Peak discharges were recorded elsewhere at approximately 1,900 other locations within distributary flow areas and along watercourses such as the Gunnery Range Wash, Sycamore Wash, Fagan Wash, Cuprite Wash, Flato Wash, and Petty Ranch Wash. In addition to modeling the 100-year event, the 10- and 25-year, 3-hour storms were modeled to help delineate significant flow corridors.

1 Introduction

1.1 Purpose

The Lee Moore Wash Basin Management Study (LMWBMS) is a flood control planning study of the Lee Moore Wash Basin. The Pima County Regional Flood Control District (PCRFCD) has identified the Lee Moore Wash Basin as a critical area with the potential for extensive future development. The LMWBMS originally included tasks to model the entire watershed with HEC-HMS to determine runoff volumes. This hydrologic modeling would then be followed by HEC-RAS hydraulic modeling to compute flow hydraulics. However, during the hydrologic and geomorphic analyses, it was determined that a relatively large portion of the study area is characterized by distributary flow. The distributary flow patterns caused standard watershed delineation and one-dimensional hydraulic modeling to be ineffective.

The purpose of this current study is to provide two-dimensional flow analysis with the FLO-2D flood routing model (FLO-2D FRM) at a level of detail sufficient for a basin-wide planning study. This report discusses the two-dimensional flow analysis conducted as a part of the LMWBMS.

1.2 Study Area

The Lee Moore Wash Basin drains an area of approximately 213 square-miles and is located entirely within Pima County. The basin covers parts of the incorporated limits of both the Town of Sahuarita and the City of Tucson. Portions of the basin are a part of the Santa Rita Experimental Range and Wildlife area (administered by the University of Arizona College of Agriculture) to the southwest and Coronado National Forest to the southeast (United States Forest Service). The Lee Moore Wash basin drains to the Santa Cruz River and is generally bounded by Old Vail Connection Road to the north, Interstate 10 to the northeast, Santa Rita Road to the south, State Route 83 to the east, and the Santa Cruz River to the west. The Lee Moore Wash basin includes multiple smaller basins which drain to washes including the Gunnery Range, Lee Moore, Fagan, Petty Ranch, Flato, and Franco Washes. Figure 1 shows the study area.

Drainage in the basin is generally towards the west and northwest, draining to the Santa Cruz River. The flow patterns vary within the basin; tributary flow occurs in the upper watershed, distributary flow occurs within the lower piedmont, and incised tributary flow occurs near the Santa Cruz River. Vegetation within the basin is typical of Sonoran Desert vegetation and is currently in good condition in most of the undeveloped areas.

The majority of the watershed is undeveloped and in mostly natural conditions with the exceptions of roads, fences, grazing, stock tanks, and utilities. However, much of the northern and western periphery and some areas within the middle are developed and are continuing to develop, primarily with residential structures.

The limits of the FLO-2D modeling are the drainage areas south of the Flato Wash, from the upper watershed down-basin (northwest) to the Lee Moore Wash, see Figure 2 This area is approximately 136 square miles.

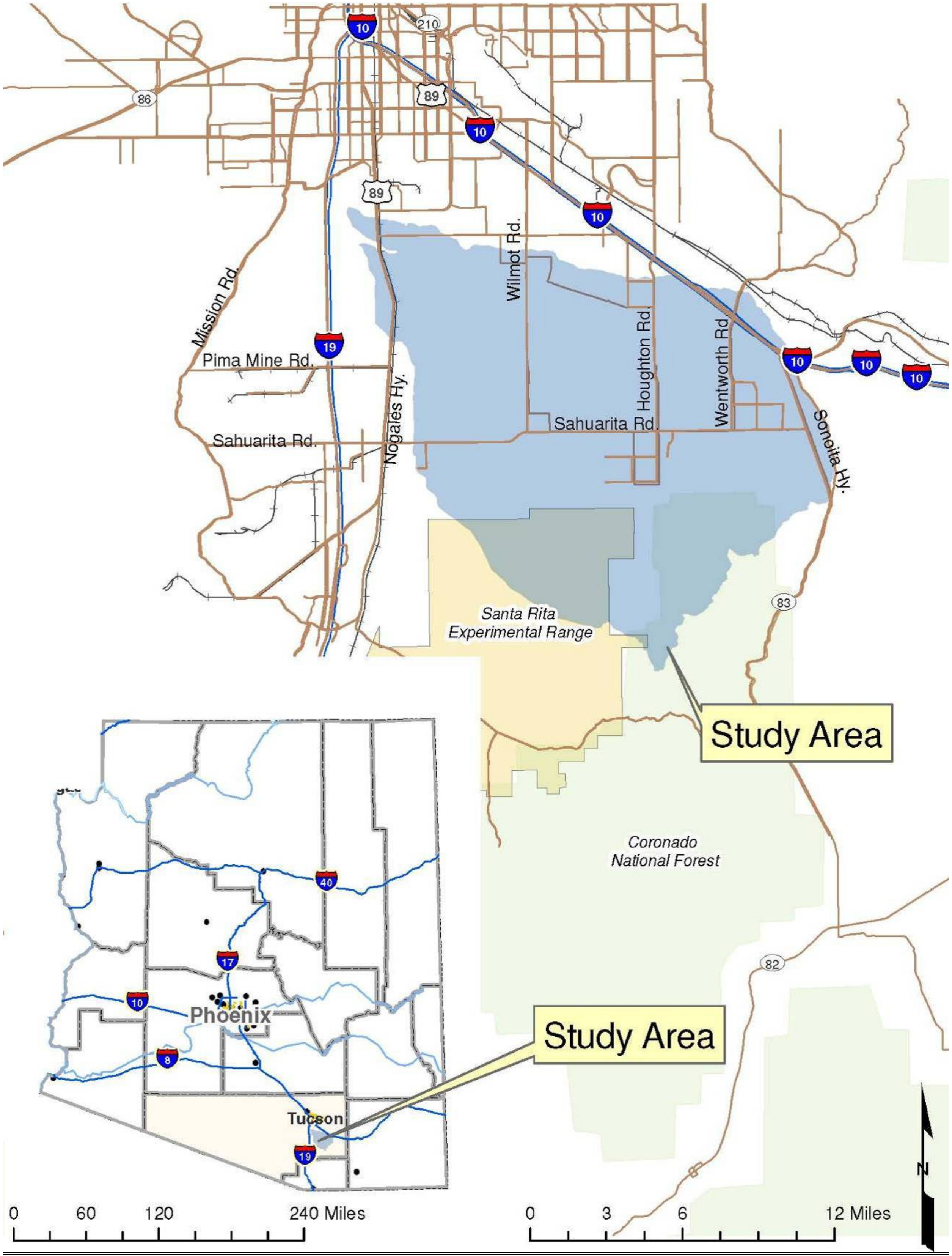

Figure 1 - LMWBMS project location map

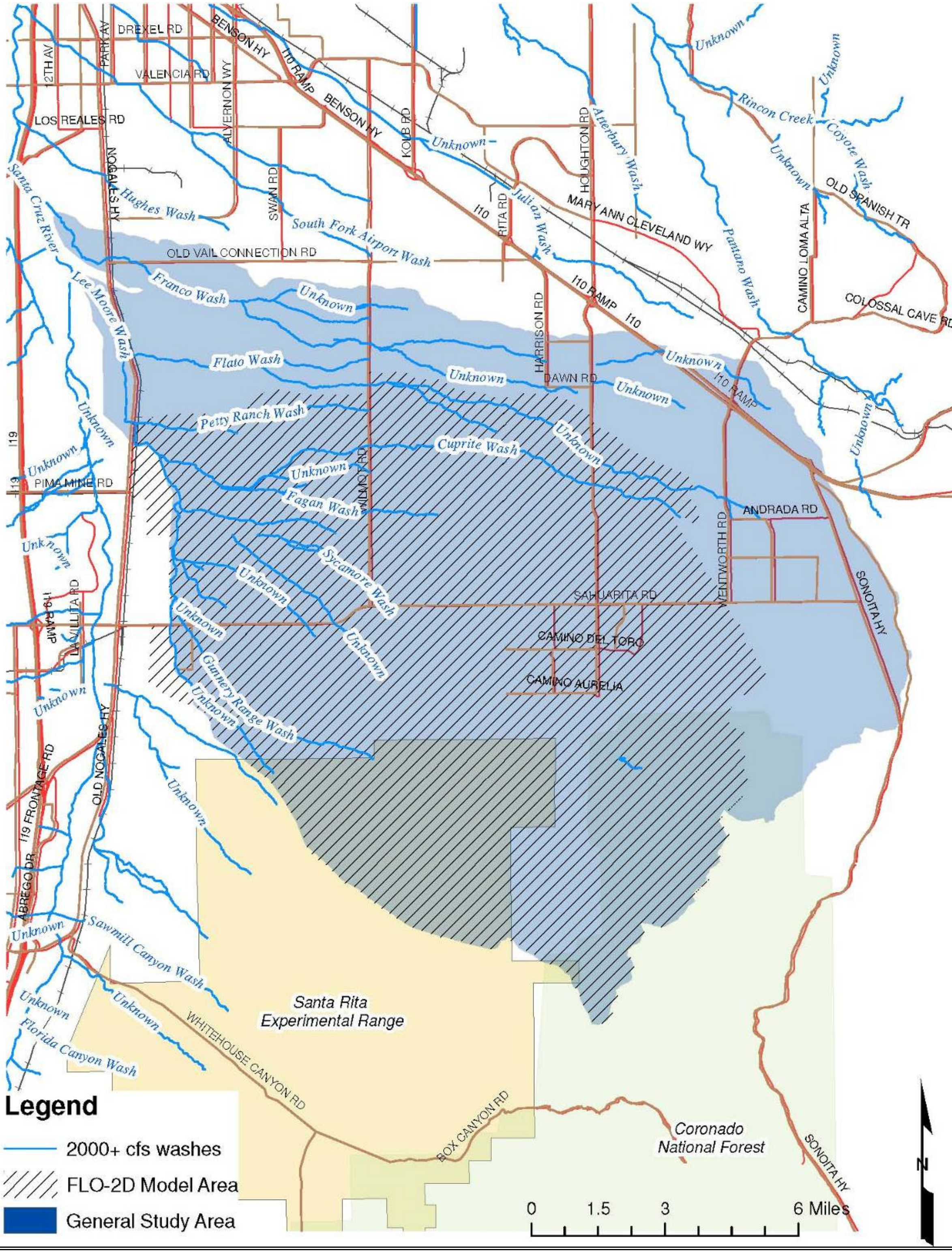

Figure 2 - FLO-2D model area

1.3 Two-Dimensional Flow Analysis Scope

JE Fuller Hydrology and Geomorphology, Inc. (JEF) prepared this report while under contract with Stantec Consulting, Inc. (Stantec). This report documents the study and results associated with Change Order 1 of Pima County contract number 16-59-S-138098-0606. The fulfillment of the scope is summarized in the following paragraphs.

Task 1 required JEF to calibrate a FLO-2D model with HEC-HMS modeling.

- ✓ **Section 5** discusses the calibration and detailed analysis is found in **Appendix E**. Further verification of results is discussed in Section 7 and Appendix G.

Task 2 required JEF to develop a single FLO-2D model of the LMWBMS for the area south of the Flato Wash, extending to the upper limit of the watershed and down to the Lee Moore Wash. This model would not be highly detailed but would be used to determine areas where more detailed modeling would be effective.

- ✓ **Section 2** provides an overview and **Appendix D** discusses the model in detail.

Task 3 included the development of models of greater detail and smaller study area than Task 2.

- ✓ **Section 6** discusses detailed models.

Task 4 was a coordination task, requiring JEF to coordinate with the FLO-2D FRM developer, PCRFCD, and Stantec to incorporate Soil Conservation Service (SCS) Curve Number (CN) methodology into the FLO-2D FRM as well as to assure that proper assumptions were made in developing the specific FLO-2D models.

- ✓ Task 4 was ongoing throughout the project.

Task 5 required JEF to prepare flood inundation and velocity maps based upon the results of the FLO-2D modeling.

- ✓ **Flood inundation** were prepared in coordination with Stantec. These have been provided separate from this report by Stantec.
- ✓ **Velocity, and depth maps** are included with this report as Exhibit 1.

Task 6 was the preparation of this summary report.

- ✓ **This report** satisfies Task 6.

2 Modeling Overview

2.1 General

The FLO-2D analysis was an iterative process which involved modeling the area multiple times and with multiple methods to determine the most appropriate results based upon calibration and engineering judgment. This section summarizes the process followed to generate the ultimate results. Individual steps are discussed in detail later in the report as necessary.

2.2 Overview

The following graphic illustrates the 100-year event modeling and map preparation steps.

Use of SCS CN verified

400 ft grid modeled, flow patterns determined

200 ft grid modeled and calibrated to HMS methodology

Study area subdivided into 7 sub-models with hydrographs from upstream sub-models input downstream

Preliminary flood and discharge maps developed and submitted to PCRFCD

Models refined to model 3- and 24-hour (100-yr) storms with rainfall depth varied between models

Results compared to HMS models

Final flood and discharge maps prepared

Figure 3 - 100-year event FLO-2D model and inundation map development steps

The following list further outlines the steps followed to develop the final flood and discharge maps provided to the PCRFCD.

1. The SCS Curve number procedure was used within the FLO-2D FRM to compute direct runoff. The computations made by the FLO-2D FRM and its grid developer program were verified before fully committing to model development.
2. The 100-year, 24-hour storm was modeled with a large-scale (relatively low grid resolution) model that had a grid size of 400 feet based upon the USGS DEM and was developed to

determine general flow patterns and computational capabilities.

3. A 100-year, 24-hour model with a 200-foot wide grid pattern was developed using the USGS DEM. Inflow from the Stantec HEC-HMS model and FLO-2D flow split models were added to direct runoff computed within the FLO-2D FRM using the SCS CN Procedure. The 100-year, 24-hour rainfall depth of 4.37 was found at the centroid of the study area and comes from NOAA Atlas 14 using the upper bound of the 90% confidence interval. The rainfall distribution followed the SCS Type I curve.
4. Three of the Stantec delineated sub-basins were selected to use in a calibration analysis. The sub-basins were modeled with the FLO-2D FRM to determine the effects of varying certain input parameters. The 100-year, 24-hour storm was the only storm modeled.
5. The results of the calibration routine were incorporated into the 200-foot grid USGS DEM model. The preliminary results were discussed with Stantec and the PCRFCD.
6. The portion of the study area within topographic coverage provided by PAG (2005) was analyzed in further detail with 100-foot grid models. This area was eliminated from the 200-foot grid model yielding a 200-foot USGS DEM model which terminates along a straight line running east and west just within the PAG coverage. This model was labeled Model 0.
7. Based upon the flow patterns from the 200-foot grid model, the PAG topographic coverage was subdivided into 6 models with 100-foot wide grids. These models receive inflow from Model 0 as well as from the Stantec HMS models and the FLO-2D flow split model "J4". The rainfall depth of 4.37 inches was used in all models.

   The study area was modeled as two-dimensional flow except where channels and berms were found to be hydraulically important. Therefore, several areas were modeled with channels and berms within the FLO-2D models, generally within the incised regions of the model area and where berms have been built.
8. Preliminary flood maps and peak discharge maps were developed based upon the detailed 100-foot grid with the 100-year, 24-hour storm. These maps were provided to the PCRFCD for review and comment. The most significant comment was that many areas appeared to have underestimated peak discharges.
9. The cause of the underestimated peak discharges was found to be primarily due to the use of the 24-hour storm. Therefore, the 3-hour storm was also modeled

   Another cause of the underestimated discharges was determined to be the use of a single rainfall depth over the study area. Consequently, both the 3-hour and 24-hour models were modeled with unique rainfall depths for each of the 100-foot grid models and the 200-foot grid model.
10. Several areas were analyzed with HEC-HMS to compare results to the FLO-2D modeling.
11. A delineation was made of areas where 100-year 3-hour peak discharges are not appropriate. The 100-year, 24-hour peak discharge is reported and delineated in these areas.
12. Final flood maps were prepared based upon the greatest discharge from the 100-year, 3-hour and 24-hour storms and the above delineation.
13. 10- and 25-yr models prepared with the 10-year event floodplain delineated.

3 SCS Curve Number Methodology

3.1 General

This section discusses the application of the SCS Curve Number (CN) methodology as it relates to the FLO-2D models along with the methods used to input the various SCS CN parameters into the models.

3.2 General Description of SCS Curve Number Methodology

The FLO-2D FRM can compute infiltration (loss) and runoff (excess) based upon rainfall and infiltration data (curve number). Within FLO-2D, each grid element is assigned a single CN, an average for the area represented by the grid element. The CN can be computed outside of the FLO-2D software suite and input via a number of methods, or can be computed with the FLO-2D Grid Developer System (GDS), the procedure used in this project. The GDS computes the CN following relationships presented within the Pima County Hydrology Procedure and requires the input of three ESRI format shapefiles;

- A shapefile which identifies the hydrologic soil group (A, B, C, or D or a combination thereof) along with the hydrologic cover (desert brush, herbaceous, etc.).
- A shapefile delineating the cover density.
- A shapefile delineating the impervious areas along with the percent impervious.

The total loss is computed based upon the rainfall depth. The initial abstraction can be computed via the generic procedure for each grid element or assigned globally. Rainfall data is entered via a depth versus time distribution table. All other FLO-2D procedures are standard.

3.3 Verification of Methodology

As this is the first use of the SCS CN methodology within the FLO-2D FRM, the various computations were checked for errors by JEF. It was verified that the GDS computes a curve number as would be calculated by hand following Pima County methodology. The functional relationships of cover density versus curve number (formulas developed that calculate CN from vegetative cover density and type) derived by the FLO-2D developers were verified with matching results and the computation of the CN by the GDS matched several hand calculations. Over 100 combinations of soil type, cover density, and impervious percentage were computed externally and with FLO-2D without significant differences in the results.

JEF reviewed the results of simplified FLO-2D models to determine if the FLO-2D FRM would compute infiltration depths matching those computed by HEC-1 or by hand. Following initial review of the model by JEF and discussion with and revision of the FLO-2D FRM by the FLO-2D developers, it was found that FLO-2D is reliable in regards to the computation of infiltration depth for a specific curve number and rainfall depth.

4 Manning's Roughness Discussion

4.1 General

FLO-2D is unique in how the roughness coefficient is handled within the calculations. This section discusses how roughness values are used in FLO-2D to help explain the calibration procedure and the seemingly low floodplain roughness coefficients used in the final models.

4.2 Floodplain Roughness

The floodplain roughness is handled through a stepped process and is defined by the:

- **Floodplain Roughness Coefficient**: Entered on the FPLAIN.DAT file and unique for each grid element, this is the basic description of roughness for flow depths **over 3.0 feet**. This coefficient can be altered automatically by applying a Limiting Froude Number.
    - ***Limiting Froude Number***: Globally assigned as FROUDL on CONT.DAT file. This automated adjustment to the floodplain roughness coefficient can be used to prevent flow from exceeding a specific Froude Number by individually adjusting the floodplain roughness for each element and each time step. FLO-2D will report on the adjustments in the FPLAIN.RGH and CHAN.RGH output files which can be reviewed and used in determining appropriate roughness coefficients.
- **Shallow Roughness Coefficient**: Assigned globally as SHALLOWN on CONT.DAT file. The minimum value is 0.1 and model will default to this if lower values are entered.
- **Depth Varied Roughness**: Global coefficient with default status of on, but can be turned off (AMANN=-99 on CONT.DAT file). Used in order "to improve the timing of the floodwave progression through the grid system" (FLO-2D Input Manual, 43).

The FLO-2D FRM applies a Manning's roughness coefficient to each grid element for each time step per the following:

Table 1 - Grid element roughness rules

Grid flow depth range (ft)	Roughness defined by	Applied roughness value
0.0<d<0.2	Shallow Roughness	n=SHALLOWN
0.2<d<0.5	Shallow Roughness	n=SHALLOWN/2
0.5<d<3	Depth Varied Roughness	$n=n_b*1.5*e^{-(0.4*d/3)}$
3<d	Floodplain Roughness	$n= n_b$ (the FPLAIN.DAT value)

Adapted from page 43 of FLO-2D Data Input Manual

4.2.1 Example Application

Figure 4 gives a graphical representation of how the model defines roughness on the floodplain. In this example:

- The shallow roughness value is 0.10.
- The depth varied roughness equation turned on.
- The floodplain roughness value is 0.030.

Per the rules in Table 1, the resulting roughness value at 1.0 feet is approximately 1.3 times the floodplain roughness value (0.039) and the roughness value at 0.6 feet is approximately 1.4 times the floodplain roughness value (0.042).

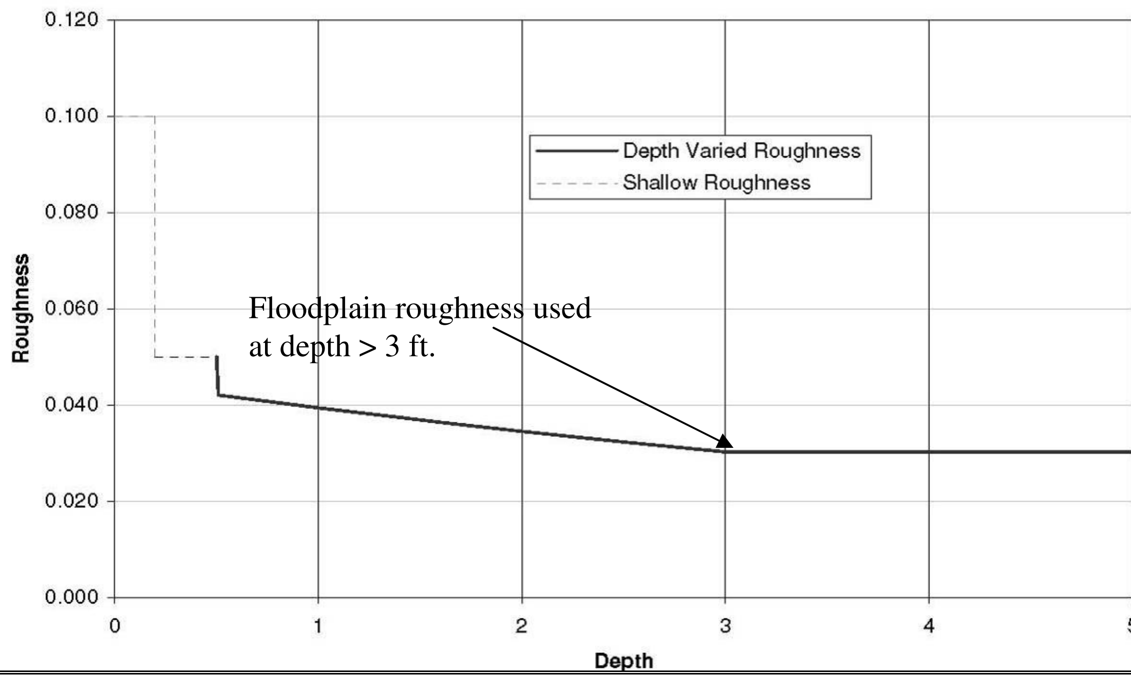

Figure 4 - Representation of depth varied floodplain roughness

One can see that an issue faced when using this methodology is that if the floodplain roughness is set high enough relative to the shallow roughness value, the model will compute an increase in the roughness value from 0.5 feet to a depth just above 0.5 feet. In the case of the floodplain roughness being 0.045 and SHALLOWN of 0.1, the roughness at 0.5 ft is 0.050 (SHALLOWN/2) but the roughness at 0.6 ft is 0.063 per the depth varied roughness equation. This may or may not be a problem depending upon the given hydraulics and the limited time flow depths are in this range.

4.3 Channel Roughness

The channel roughness value is treated separately from the floodplain roughness with similar methods. A limiting Froude Number can be assigned for each channel element. Additionally, a depth variable roughness equation is used by FLO-2D. The equation varies the roughness from the assigned roughness value at bank full flow to some greater value based upon a user defined coefficient ($0 < r2 < 1.2$). The greater the value of the coefficient, the greater the variation in roughness. Figure 5 is a graphical representation of the roughness equation relationship with a base (bank full) roughness value of 0.035 and a bank full depth of 4 feet.

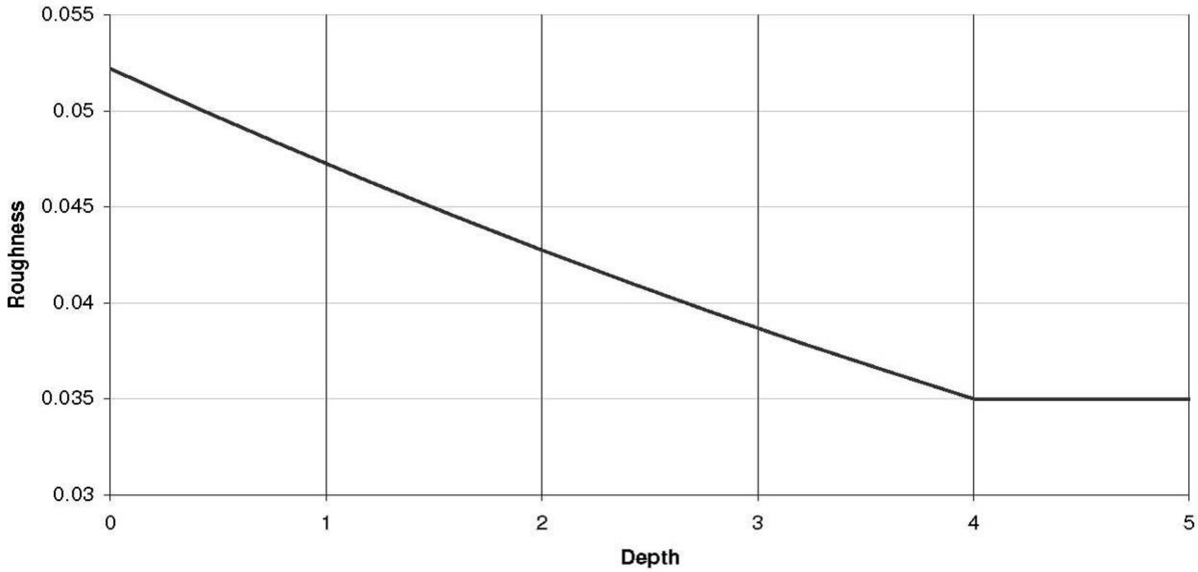

Figure 5 - Representation of depth varied channel roughness

One problem noted by this user with the depth varied channel roughness equation occurs when channel cross sections are cut which are much deeper than the flow depth. Consider the situation of a cross section cut that has banks 8 feet above the flow line but a maximum water surface of 3 feet. The model will assume that bank full depth is 8 feet and therefore the roughness value at 3 feet of flow depth may be exceedingly high. This situation occurs in many of the constructed channel areas and highly incised areas. For this reason, the depth variable equation coefficient is set on the low side of the range of values, between 0.2 and 0.4.

5 Calibration

5.1 General

This section discusses the calibration procedures with summary results and conclusions. Detailed discussion is included within Appendix E and has been previously presented to the PCRFCD. Note that calibration was performed for the 100-year, 24-hour model.

5.2 Calibrated Variables

In order to calibrate the model, the input variables most appropriate to adjust include;

- Floodplain roughness coefficient.
- Shallow flow roughness coefficient.
- The use of depth variable roughness.

Other factors which may affect peak discharge are: surface detention depth (the minimum depth of flow before FLO-2D routes runoff), grid size, and limiting Froude Number. While it is desired to calibrate the FLO-2D model to HEC-HMS procedure models, it is not realistic to expect a FLO-2D model of this scale to generate results exactly as would be predicted with HEC-HMS. One of the primary issues with calibrating the model is the fact that the FLO-2D FRM is a physical process model which incorporates the coupled effects of flow hydraulics and hydrograph generation. Therefore, adjusting a parameter such as roughness in order to obtain a desired peak discharge can have an effect on the predicted flow hydraulics.

Several calibration models have been developed from sub-basins within Petty Ranch, Cuprite, and Franco Washes. There are 5 basic Petty Ranch models which model the same area differently. Similarly, there are 4 basic Cuprite and 5 basic Franco models. Within the above models, individual variables were isolated yielding over 100 sub-models. The variables changed were:

- The floodplain roughness coefficient, from **0.01 to 0.04**.
- The use of the depth variable roughness equation, **on or off**.
- The shallow flow roughness coefficient, **0.10 to 0.25**.
- The grid element size, **85 and 200 feet** for Petty Ranch and Franco, **85 feet** for Cuprite.

Peak discharges computed by HEC-HMS for these areas were compared to those computed by FLO-2D. For all FLO-2D models, the elevation data was obtained from the available PAG DEM/DTM data and the limiting Froude Number was set to 0.85. Figure 6 shows the model limits relative to the study area. Table 2 summarizes the basic geometry of the model limits.

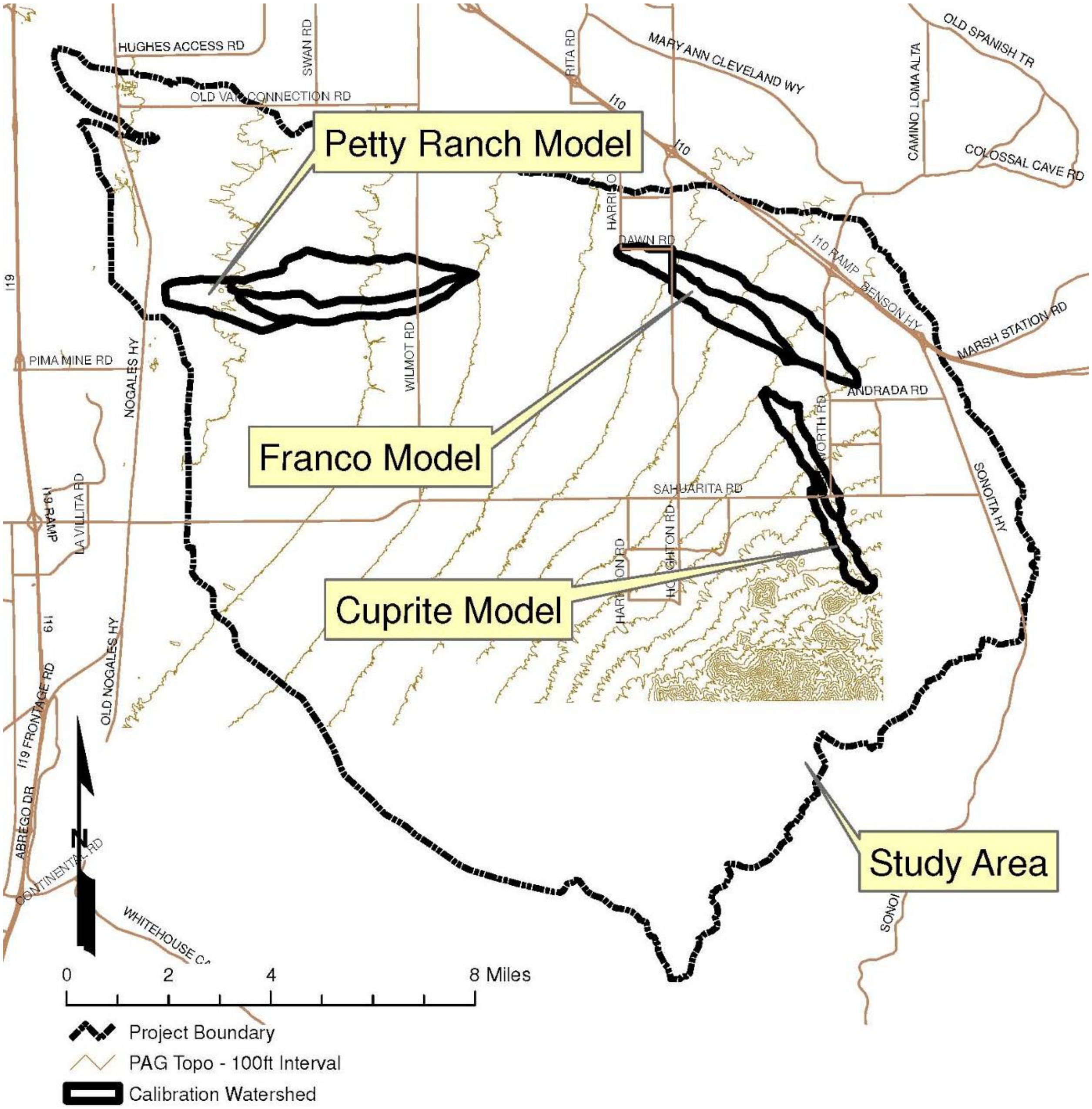

Figure 6 - Calibration model limits

Table 2 - Calibration model geometry

Model	Area (sq mi)	Length (ft)	Ave. Width (ft)	Ratio L:W	Elev. Change (ft)	Ave. Slope (ft/ft)
Petty Ranch	5.388	32,100	4,680	6.9	260	0.008
Franco	3.697	28,900	3,570	8.1	390	0.013
Cuprite	1.468	23,500	1,740	13.5	840	0.036

5.3 Calibration Model Observations

Detailed results from the calibration procedure are included within Appendix E. Review of the calibration model results leads to mixed conclusions. Somewhat predictable results can be obtained when altering certain variables, while altering other variables will not yield predictable results. The reason for this is that the variables are linked, for example changing the floodplain roughness alters the flow depth. If the flow depth is reduced via a lower floodplain roughness coefficient, then the model may use the shallow roughness coefficient. Likewise, if the depth varied roughness equation is used, the roughness of a grid element may change many times during a model run.

In general, the FLO-2D FRM predicted peak discharges less than what HEC-HMS predicted while predicting time of peak values slightly greater than what HEC-HMS predicted. The reasons for this are arguable. The HEC-HMS model requires simplified input calibrated to watersheds modeled elsewhere which may not fully account for the local watershed geometry and hydraulic response. Furthermore, the FLO-2D model may overestimate attenuation as the detail of the primary flow paths is lost in the development of the grid. This may be rectified if the channel option is used, but this adds greatly to the level of detail required when developing the models. Table 3 summarizes the recommendations based upon the calibration with HEC-HMS.

Table 3 - Summary of FLO-2D to HEC-HMS calibration recommendations

Variable	Recommendation
Depth varied roughness equation	Turn on (leave on as default is on)
Grid element size	Use smallest size reasonable.
Floodplain roughness coefficient	Use 0.030 to 0.035. May use 0.040 for smaller grid sizes. Use a smaller value when larger grid sizes are used. Avoid values less than 0.030 unless justifiable and within primary flow corridors.
Shallow roughness coefficient	Use appropriate value in conjunction with the terrain and the floodplain coefficient used. 0.010 may be most applicable for Lee Moore Wash study area.

The final recommendation based upon the calibration procedure is the threshold flood mapping depth discussed within Appendix E. It should be noted that the depth discussed is an average depth over a grid element and does not account for more localized flow depths. This explains why using a depth as great as 0.5 feet places only 10 percent of the study area within the mapped flood limits, an arguably low number considering the sheet flow documented within the area. A depth of 0.03 feet places about 90 percent of the study area within the flood limits. A more reasonable value is a depth of around 0.2 feet and was the guideline in delineating flood inundation for this project.

6 Detailed 100-year Event Models

6.1 General

This section documents the detailed 100-year event FLO-2D models prepared for this project. These models were used to prepare the flood inundation maps (submitted by Stantec separately).

6.2 Model Geometry

The study area was sub-divided into 7 sub-models to reduce individual model size and runtime. The model limits are shown on Figure 7.

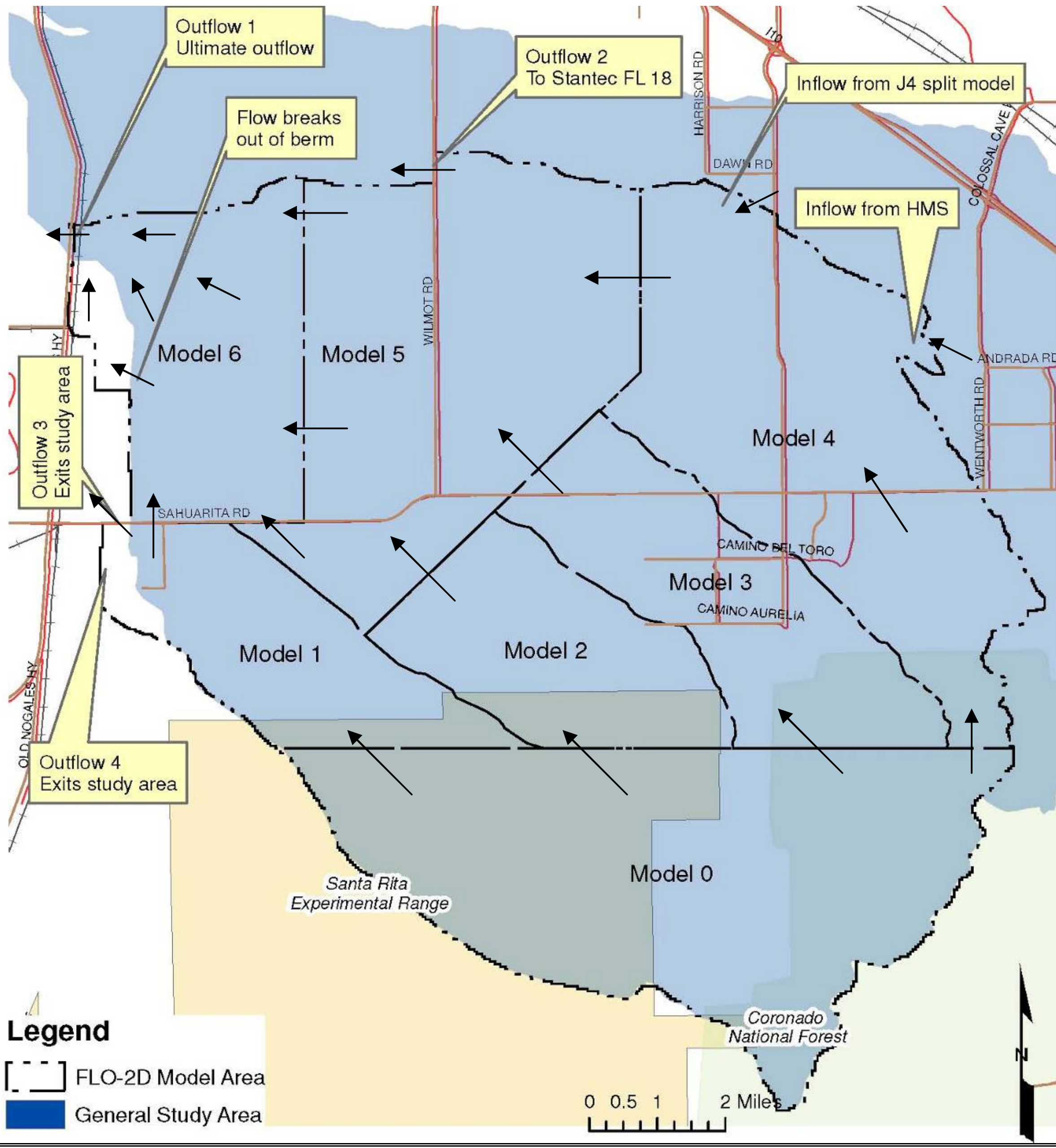

Figure 7 - Detailed sub-model boundaries

Model 0 uses the elevation data from USGS DEM and has a 200-foot grid. The remainder of the study area was sub-divided into 6 models, all with 100-foot grid spacing using PAG elevation data.

Note that it was necessary to subdivide the model as there are over 311,000 grid elements on two different elevation models. In addition, external hydrographs with large volumes were added to the model ($V_{100\text{-}24}$=3,470 ac-ft), direct runoff was computed, over 650 grid elements were modeled with channel sections, and over 30 grid elements were modeled with levees. Finally, the shape of the basin causes over 21,600 cfs and 18,700 ac-ft of runoff to pass through the space of 200 feet of width at the ultimate outflow point. All of the above increase runtime and would have exceeded available computational resources if modeled in one model.

6.3 Precipitation Depth and Distribution

The 100-year 3-hour and 24-hour storms were modeled with the rainfall distribution and depth entered on the RAIN.DAT FLO-2D file. Rainfall data was obtained from NOAA Atlas 14 using the upper bound of the 90 percent confidence interval (the upper bound data was used based on direction from the PCRFCD). The 3-hour storm followed the most intense portion of the SCS Type II curve using a distribution provided by the PCRFCD and verified by JEF. The 24-hour storm was modeled with the temporal distribution of rainfall obtained from SCS Type I coordinates. For both distributions, the rainfall begins at 12 hours as the Stantec HEC-HMS models have a start time of 12:00. The following table summarizes the 100-year 3-hour and 24-hour rainfall depths used in the 7 models.

Table 4 - 100-year precipitation depths

Model	Area	Centroid		100-year depth (upper bound of 90% confidence interval)	
	(sq mi)	Longitude	Latitude	3-hour	24-hour
0	33.21	31.880	110.802	3.74	4.83
1	10.88	31.930	110.900	3.23	4.19
2	11.15	31.928	110.831	3.35	4.40
3	13.95	31.939	110.788	3.45	4.50
4	26.16	31.975	110.763	3.42	4.45
5	26.69	31.993	110.856	3.24	4.21
6	14.29	31.995	110.918	2.87	3.76
Total	136.33				
Weighted				3.39	4.40

6.4 Roughness Values

The floodplain roughness coefficient was assigned by geographic location (based upon the calibration); **0.030** within piedmont areas and **0.040** on hillslope areas. The shallow roughness coefficient was set to **0.10** and the limiting Froude Number (floodplain) was set to **0.85**.

It is noted that the above floodplain roughness coefficients may be interpreted as low considering the terrain. However, recall the rules discussed within Table 1 and note that this roughness coefficient applies to flow depths over 3 feet. Review of the flow depths reported by FLO-2D indicates that the vast majority of time steps occur with flow depth less than 0.5 feet, causing the model to use the shallow roughness coefficient.

A good indication that any roughness coefficient is appropriate is analysis of the Froude Number. This can be accomplished with the FLO-2D FRM via limiting the Froude Number, thereby forcing FLO-2D to adjust the assigned floodplain roughness values up to limit the Froude Number to some maximum value. Therefore, a preliminary model was executed with an extremely low global floodplain roughness coefficient of 0.010, the limiting Froude Number set to 0.55, and depth variable roughness turned on. The resulting adjusted floodplain coefficient values (reported by FLO-2D within the FPLAIN.RGH file) were typically less than 0.035 on the piedmont and less than 0.050 on the hillslopes. In reality, flow on the hillslopes is likely critical with a Froude Number near 1. Tests were performed on the piedmont areas and the Froude Number is realistically between 0.3 and 0.8, depending upon location. This test supports the values used for floodplain roughness coefficients.

6.5 SCS Curve Number Inputs

Stantec originally developed SCS CN shapefiles for use in the HEC-HMS model. These files were obtained by JEF. Where the FLO-2D model area extended outside of the original delineation by Stantec, the parameters were assigned by JEF following procedures used by Stantec. The methods employed by Stantec assigned the hydrologic cover based upon land use (development type and density) and other parameters. Cover density was set to 20 percent at elevations below 4,000 feet and 30 percent above 4,000 feet.

6.6 Inflow and Outflow Locations

Models 1 through 4 receive inflow hydrographs from Model 0 and route this flow downstream along with runoff generated from rainfall on the modeled surface. Model 4 also receives runoff hydrographs from HEC-HMS modeling and the J4 flow split model. Along with modeling rainfall runoff, Model 5 receives inflow hydrographs from Models 2, 3, and 4. Model 6 adds local runoff to inflow hydrographs from Models 1 and 5. See Appendix F for further details including flow routing diagrams.

The FLO-2D FRM will model the hydraulics of outflow elements but does not model the rainfall falling on these elements. There is consequently a one cell overlap between models to account for all of the rainfall volume within the study area. Outflow hydrographs are recorded by FLO-2D in OUTNQ.DAT for floodplain elements and within HYCHAN.DAT for channel elements. These hydrographs were entered into the INFLOW.DAT file. An automated script was developed by JEF to build the INFLOW.DAT files.

Outflow from the model area is recorded along Sahuarita Road, from Model 1. Breakout flow from Model 5 is recorded along Wilmot Road and Stantec recorded this as inflow into the HEC-HMS model. Finally, outflow from Model 6, at the Union Pacific Railroad Bridge over the Lee Moore Wash, is recorded as inflow into Stantec's HMS model.

Breakout flow was found to occur within Model 6 along a berm as labeled on Figure 7. Runoff at this location drains west and then north to reenter the Lee Moore Wash. This breakout was not modeled on the large-scale model and is not shown on Pima County GIS flow lines but it was however modeled within the detailed models.

7 100-year Event Results and Verification

7.1 General

This section discusses the 100-year event results and an analysis to verify the results.

7.2 Detailed Model Results

The peak discharges and volumes entering and exiting the study area are summarized in the following table. See the flood inundation maps for more discharge information.

Table 5 - 100-year event summary results

	Peak Discharge (cfs)		Time of Peak* (hr)		Volume (ac-ft)	
	3-hr	24-hr	3-hr	24-hr	3-hr	24-hr
Inflow						
Rainfall					24,625	32,012
Total inflow hydrograph					2,489	3,472
Inflow from Stantec J9	*9,840*	*5,770*	*3.3*	*11.4*	*1,750*	*2,471*
Inflow from Stantec J11	*3,150*	*1,840*	*2.8*	*11.3*	*519*	*746*
Inflow from Stantec CU-J1	*1,240*	*690*	*2.5*	*10.9*	*149*	*219*
Inflow from J4 flow split	*540*	*230*	*3.8*	*12.2*	*71*	*37*
Rainfall and inflow sum					27,114	35,485
Loss volume						
Infiltration and Interception					10,401	11,216
Storage					2,666	2,666
Total loss					13,066	13,882
Outflow						
Total outflow					14,126	21,655
Outflow 1	*21,910*	*20,210*	*7.8*	*17.2*	*12,109*	*18,765*
Outflow 2	*2,940*	*2,120*	*5.6*	*14.0*	*1,045*	*1,369*
Outflow 3	*1,450*	*1,420*	*6.1*	*15.9*	*732*	*1,148*
Outflow 4	*430*	*410*	*5.6*	*15.6*	*240*	*373*

** Reported time of peak values represent time from the beginning of rainfall.*

Approximately 1,900 flow recording cross sections were coded into the FLO-2D models. Shapefiles representing the extents of these have been prepared and included within this report for use by the PCRFCD. The provided cross sections record peak discharge, flow volume, time of peak, and other information for the 100-year 3- and 24-hour storms. The flood inundation maps also show these cross sections where the peak discharge recorded exceeds 100 cfs. See the table within Appendix C for more detail regarding this shapefile.

7.3 Discharge Verification

Several areas within the FLO-2D study area have been delineated using normal watershed delineation methods with runoff computed by HEC-HMS. These verification area sub-basins are the most tributary of the study area to assure that the runoff computed within FLO-2D is local and not significantly impacted by upstream flow splits. The intent was to provide comparative values for discharge, time of peak, and runoff volume to analyze the appropriateness of those values predicted by FLO-2D. The locations of the sub-basins are shown on Figure 8.

The analysis generated results similar to the calibration procedure discussed within Section 5: FLO-2D consistently predicts lower peak discharge values than HEC-HMS. Runoff ratios between the methods from the 19 sub-basins are shown in Table 6. Graphical representation of the predicted peak discharge versus drainage area are shown on Figure 9 and Figure 10. Further detailed results can be found within Appendix G.

Table 6 - Ratios of FLO-2D to HEC-HMS runoff values, 100-year event

Test Area	Area (sq mi)	Discharge ratio*		Time to peak ratio*		Volume ratio*	
		3-hour	24-hour	3-hour	24-hour	3-hour	24-hour
2-5	0.056	0.75	0.81	0.99	1.02	0.96	1.01
2-2C	0.067	0.67	0.70	0.99	1.00	0.97	1.06
2-4A	0.074	0.60	0.83	1.08	2.18	1.82	1.98
2-4C	0.088	0.83	1.04	0.84	1.01	1.03	1.11
2-4B	0.113	0.67	0.73	1.08	2.17	1.51	1.50
5-3	0.116	0.63	0.76	1.16	1.01	1.00	1.05
2-3A	0.219	1.25	1.43	0.94	0.99	0.87	0.91
2-2A	0.489	0.67	0.75	1.02	1.01	0.55	1.27
4-2	0.511	0.85	0.86	1.10	1.01	0.85	0.89
4-3	0.590	0.99	0.93	1.04	1.02	0.94	0.97
5-2	0.643	0.95	0.84	1.07	1.03	0.80	0.87
7-2	0.668	0.80	0.85	1.14	1.03	0.90	0.96
4-1	0.800	1.76	0.97	1.06	1.01	0.88	0.91
1-1	0.813	1.07	0.81	1.03	1.02	0.75	0.78
6-1	0.936	0.61	0.71	1.14	1.03	0.87	0.91
2-2B	0.970	0.61	0.69	1.14	1.06	0.55	1.28
7-1	1.034	0.82	0.82	0.97	1.02	0.83	0.89
J2-2	1.459	0.58	0.66	1.12	1.05	0.81	0.87
5-1	1.625	1.09	1.09	1.02	1.00	0.86	0.90
J4-4	1.725	0.81	0.82	1.14	1.03	0.79	0.85
2-3A&B	1.747	0.67	0.77	1.05	1.03	0.83	0.90
1-2	2.869	1.09	1.12	0.98	1.00	0.92	0.97
3-1	7.760	0.78	0.93	0.97	1.03	0.82	0.89
Average	**1.103**	**0.85**	**0.87**	**1.05**	**1.12**	**0.92**	**1.03**

** Values equal FLO-2D result / HEC-HMS result.*

Figure 8 - Verification sub-basin location map

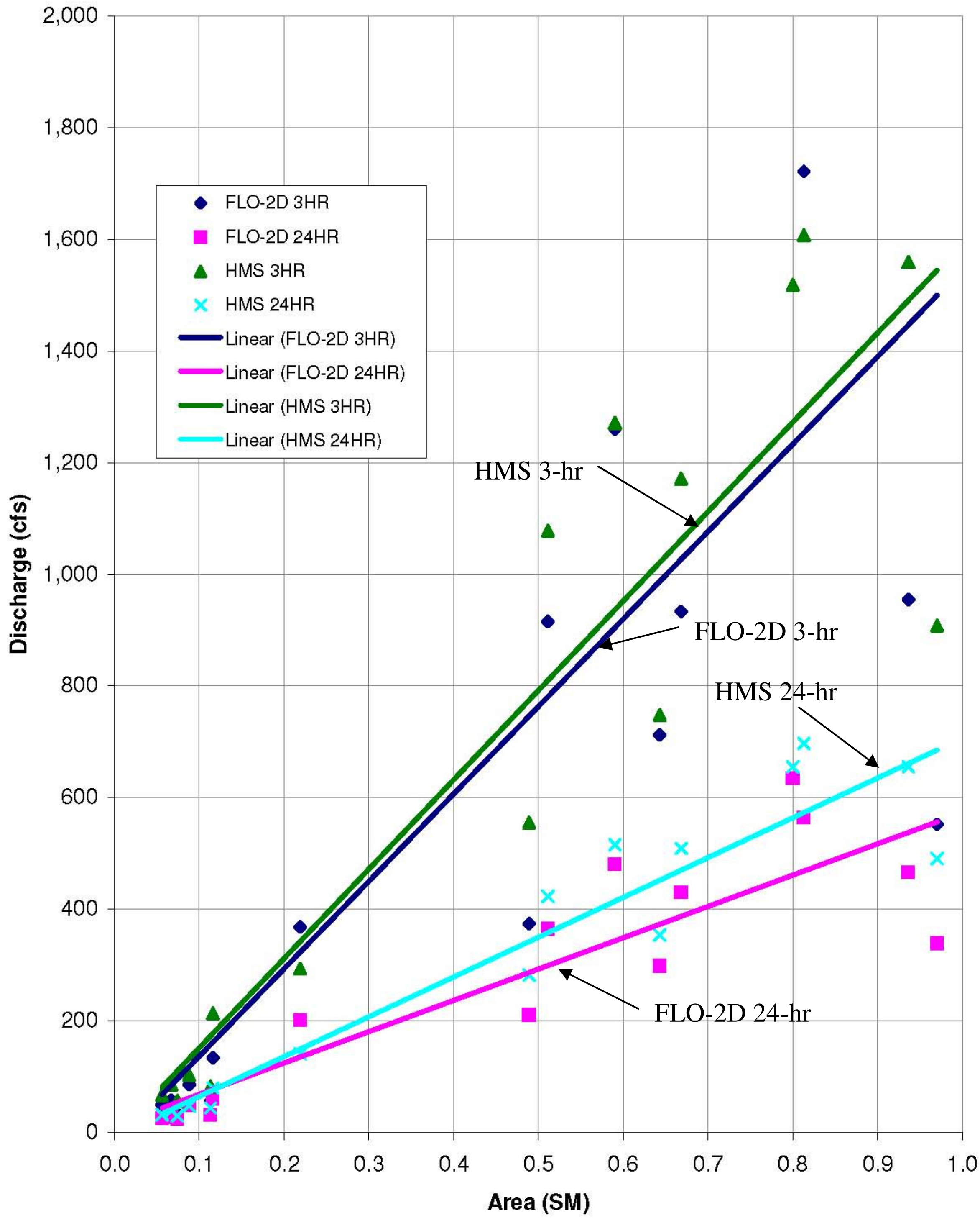

Figure 9 - Comparison of 100-yr discharge vs. drainage area, FLO-2D and HEC-HMS, DA < 1sq mi

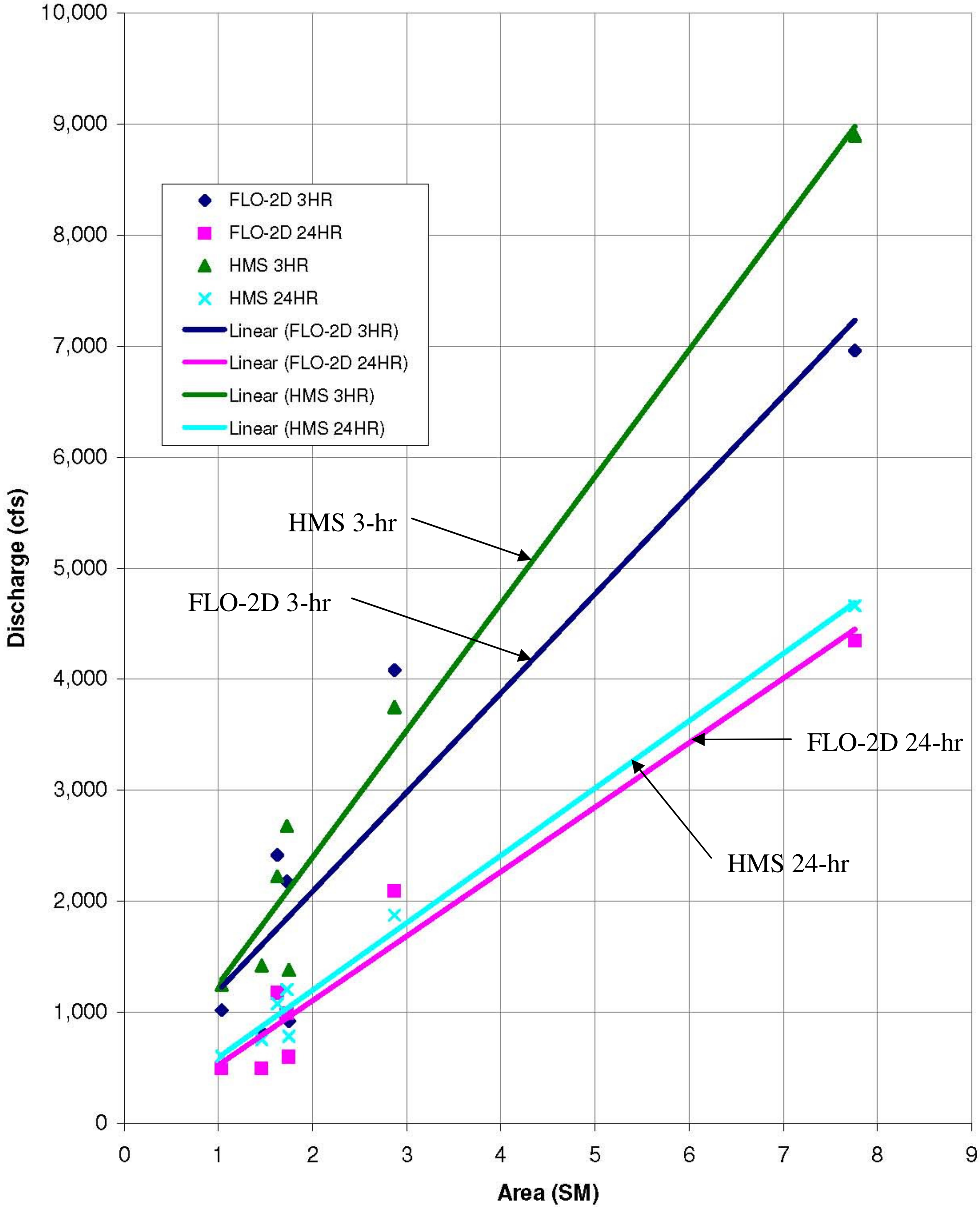

Figure 10 - Comparison of 100-yr discharge vs. drainage area, FLO-2D and HEC-HMS, DA > 1sq mi

7.4 1988 HEC-1 Model

The 1988 Pima County Department of Transportation and Flood Control District report "Hydrologic Investigation for the Lee Moore Wash Watershed, Pima County, Arizona" documented a HEC-1 model of the same study area. The HEC-1 model computed peak, 100-year, 24-hour discharge values comparable to those from this study as shown in the following table. See Figure 9 for locations of the points in Table 7. Also see Plate 2 for corresponding key concentration points.

Table 7 - Comparison of discharges between FLO-2D model and 1988 HEC-1 model

Point ID	Corresponding Plate 2 Key Concentration Point	Watercourse	1988 HEC-1 Model Q-100,24 (cfs)	FLO-2D Peak Q 100-yr, 3-hr (cfs)	FLO-2D Peak Q 100-yr, 24-hr (cfs)	FLO-2D Cross Section
-1-	Breakou 1	Gunnery Range above Lee Moore Wash	5,736	4,630	4,480	6-121
-2-	n/a	Lee Moore Wash below Gunnery Range Wash	5,207	n/a	n/a	n/a
-3-	SC13	Sycamore Canyon above Lee Moore Wash	7,793	7,260	6,220	6-168
-4-	LM1	Lee Moore Wash below Sycamore Canyon Wash	12,554	7,080	6,150	6-052
-5-	FA5	Fagan above Lee Moore Wash	7,817	9,230	7,390	6-062
-6-	LM5	Lee Moore Wash below Fagan Wash	19,814	12,830	10,850	6-018
-7-	CU4	Cuprite above Lee Moore Wash	3,171	8,900	6,750	6-081
-8-	PR4	Petty Ranch above Lee Moore Wash	1,103	1,780	1,070	6-141
-9-	LM8	Lee Moore Wash below Gunnery and Fagan	n/a	20,860	18,980	6-019
-10-	LM9	Lee Moore Wash below Petty Ranch Wash	19,711	21,910	20,210	6-001

The discrepancies at Point ID 1, 4, and 6 are significantly due to the modeling along the Gunnery Range Wash: the FLO-2D model routes flow from Gunnery Range Wash west, crossing a location where the berm does not provide containment, and combines this breakout flow downstream of the Fagan Wash, back into the Lee Moore Wash while this breakout was not accounted for in the HEC-1 model (see the different flow path delineations on Figure 9). The discrepancy at Point ID 7 may be due to modeling of flow splits upstream within the FLO-2D model not done within the HEC-1 model.

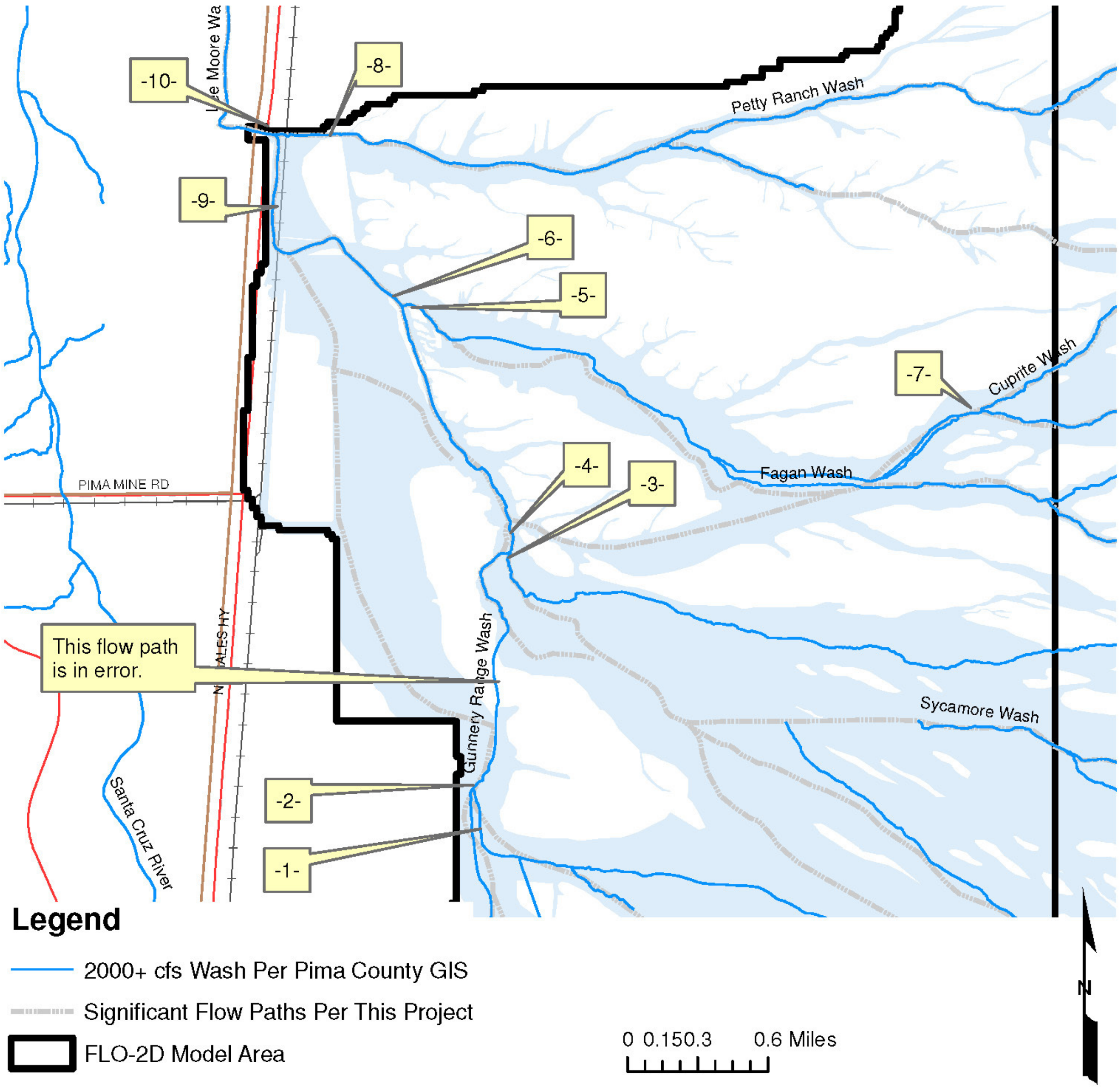

Figure 11 - Location map for comparison of discharges between FLO-2D model and 1988 HEC-1 model

8 Delineation of 100-year Event Floodplain

8.1 General

This section briefly documents the delineation of the 100-year event floodplain and the determination of the dominant discharge to report from the 100-year, 3- and 24-hour event models at different locations.

8.2 3-hour versus 24-hour Discharge

The vast majority of the study area has peak discharges which are greater during the 3-hour storm simulation, even at the most downstream end. The dissimilarity between the peak discharges in the major threads is not significant in most cases (note the similarities between the discharges at the outflow points) and the 3- and 24-hour storm models place similar quantities of land within flood inundation areas. However, locations were found where the 3-hour discharge may be unrealistic. Therefore, it was decided to report and delineate to the greater of the 3-hour and 24-hour storms up to a certain threshold. To this end, it was decided that a drainage area of 10 square miles is a reasonable cutoff as it is unlikely that the 3-hour storm will be the dominant storm in areas greater than this.

To facilitate this methodology, a calculation was performed to estimate the generic runoff volume from 10 square miles. Any location where a volume is recorded in excess of this is assumed to have more than 10 square miles of tributary drainage area. Based on an assumption of an average curve number of 85.2 and average 100-year, 3-hour rainfall depth of 3.39 inches, the threshold volume is 1,000 acre feet of runoff. Flow recording cross sections with this volume were highlighted and a final delineation was made by hand which included all of the highlighted cross sections and others based upon judgment. The delineation (Figure 12) basically includes the Flato and the Cuprite Washes as well as the incised portions of the Gunnery Range and Lee Moore Washes. All reported peak discharges within this area are based upon the 24-hour model.

8.3 Floodplain Delineation

Detailed flood mapping was done only within the PAG coverage, within the limits of Models 1 through 6. The flood inundation maps were delineated by hand based upon the peak discharges predicted by FLO-2D using the automated mapping tools of FLO-2D Mapper as a guide. In general, delineation was done in areas where peak discharges of over 100 cfs were recorded. Other areas were delineated where judgment indicated either the FLO-2D runoff estimate may be low or no cross section was present but runoff may be over 100 cfs. Normal depth cross sections were modeled in many locations to fine tune the flood limits. The final delineation indicates approximately 48 square miles of the study area (within PAG coverage) is prone to 100-year flood inundation.

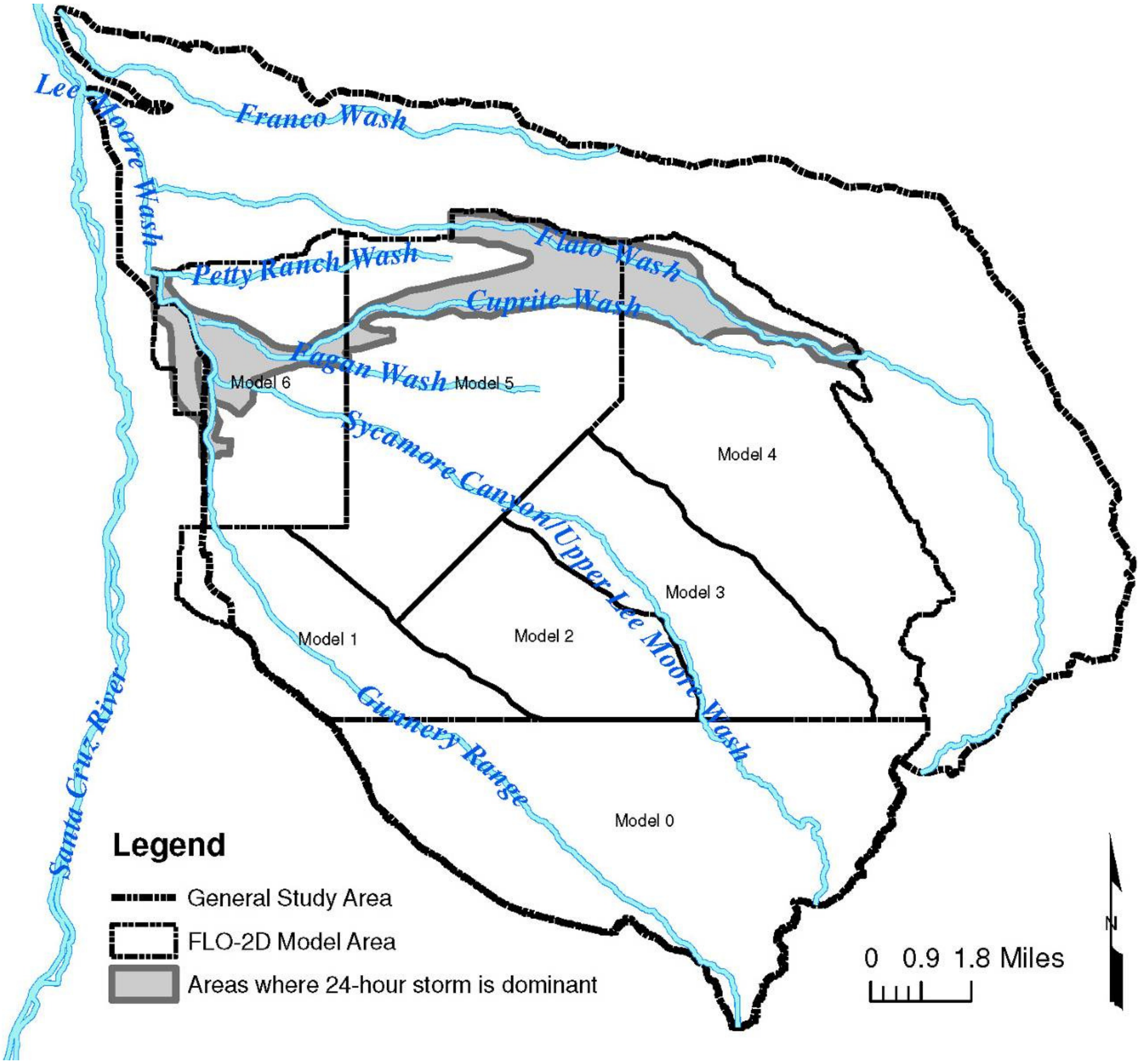

Figure 12 - Map of area where the 100-year, 24-hour discharge is dominant

9 10-year and 25-year Event Models

9.1 General

During the course of the overall planning study, it was decided that a technical approach to delineating flow corridors was necessary. For this reason, the 10- and 25-year events (3-hour duration) were modeled with the 10-year event floodplain selected as a guide for flow corridor delineation (performed separately by Stantec).

9.2 Model Input

The 100-year, 3-hour simulation models were revised to reflect the 10- and 25-year rainfall depths. Hydrographs for the Flato and Cuprite Washes were provided by Stantec. The Franco Wash J4 flow split was not modeled as its influence on the overall floodplain is minimal. No other revisions, calibrations, or verifications were performed.

9.3 Results

Table 8 summarizes runoff. 10-year event flood limits have been delineated where 10-year discharge exceeds 100 cfs (provided in shapefile format and shown on Plate 2). The flow recording cross section shapefiles document the 10- and 25-year runoff values.

Table 8 - 10-year and 25-year event summary results

	Peak Discharge (cfs)		Time of Peak* (hr)		Volume (ac-ft)	
	10-yr	25-yr	10-yr	25-yr	10-yr	25-yr
Inflow						
Rainfall					15,839	19,119
Total inflow hydrograph					1,225	1,645
Inflow from Stantec J9	*4,740*	*6,460*	*3.5*	*3.4*	*898*	*1,199*
Inflow from Stantec J11	*1,460*	*1,990*	*3.0*	*2.9*	*256*	*348*
Inflow from Stantec CU-J1	*560*	*790*	*2.6*	*2.5*	*71*	*98*
Rainfall and inflow sum					17,064	20,764
Loss volume						
Infiltration and Interception					8,833	9,528
Storage					2,649	2,662
Total loss					11,482	12,190
Outflow						
Total outflow					5,461	8,404
Outflow 1	*4,450*	*8,990*	*10.3*	*9.9*	*4,767*	*7,299*
Outflow 2	*980*	*1,480*	*6.8*	*6.1*	*427*	*604*
Outflow 3	*270*	*550*	*11.5*	*9.1*	*196*	*376*
Outflow 4	*80*	*200*	*11.7*	*8.5*	*53*	*125*

** Reported time of peak values represent time from the beginning of rainfall.*

10 Summary, Conclusions, and Recommendations

This report has provided the documentation and results from a two-dimensional flow analysis of the Lee Moore Wash using the FLO-2D FRM. In summary:

- Detailed FLO-2D models were prepared based on the 2005 PAG DTM and DEM data with flood limits delineated to 2-foot contour interval topography.
- The 100-year, 3-hour and 24-hour general storms were modeled with the greatest discharge reported on the flood inundation maps (except in major flow corridors, where the 24-hour discharge is reported).
- Rainfall data was from the upper bound of the 90% confidence interval.
- 100-year flood limits were delineated and are represented on the accompanying flood maps and are also included in the attached digital files.
- 10-year flood limits were delineated and included in the attached digital files.
- FLO-2D models were calibrated to HEC-HMS models within reasonable constraints. Results from the modeling have been verified at several locations against HEC-HMS modeling.
- The FLO-2D modeling indicates that approximately one-half of the study area is prone to flood inundation during the 100-year event.

10.1 Accuracy of Results

The various comparisons of FLO-2D and HEC-HMS models indicate that the FLO-2D FRM, on average, predicts discharges that are approximately 15% lower than those predicted by HEC-HMS. The HEC-HMS model is an accepted methodology, but HEC-HMS results should not be considered the "correct" results but rather a baseline value to compare other methods to. Much of the reduction in peak discharge by FLO-2D may be accounted for by modeling storage and attenuation that is not fully accounted for with HEC-HMS. The computation of time of concentration for the HEC-HMS model is an issue which may alter the results as this computation requires user assumptions and judgment and is based on calibration to watersheds outside of the study area. Considering the broad scale of this project, the FLO-2D results are valid and useful for this planning study.

That said, when using the FLO-2D predicted peak discharges, time of peak, or other data, it is important to understand that the results may be less conservative than those generated by other methods (although not necessarily less accurate or incorrect). Considering the modernity of this methodology and that the discharges generated by this study may guide future regulatory action, PCRFCD may want to consider the appropriateness of the results and the potential for a factor of safety of say 1.10 to 1.15 for the peak discharges. Furthermore, because FLO-2D consistently predicted a higher time of peak, a factor of safety may be applicable when combining FLO-2D generated hydrographs with HEC-HMS hydrographs.

A factor of safety may be most appropriate within smaller drainage areas. Larger drainage areas, specifically where major watercourses join, may not need this considering that the FLO-2D study area assumed a stalled storm over the entire basin without aerial reduction.

It should be stressed that the 3-hour storm is too long of a duration for many smaller drainage areas and individual studies must account for the runoff from a shorter duration, more intense storm. Smaller areas studied with the Pima County PC Hydro program (or similar method) will certainly have predicted peak discharges exceeding those presented within this study.

Finally, a comment on the use of the flood inundation maps. These maps were prepared for planning and management purposes from a broad scale perspective. Use of the flood inundation maps in setting floor elevations or determining if an individual parcel is in or out of a flood plain is cautioned and may not be recommended. A lot or project-specific drainage analysis will likely be necessary depending upon the given situation.

10.2 Unmodeled Breakout Flow

Outflow from the model area was recorded along Sahuarita Road at locations labeled Outflow 3 and Outflow 4 and this flow was not modeled downstream of Sahuarita Road. In reality, some portion of this flow will continue north to rejoin the Lee Moore Wash channel flows, potentially adding another 10% or more to the peak discharge under the railroad bridge. However, this flow that breaks out enters into the Santa Cruz River floodplain and much of this area has already been mapped as FEMA floodplain. Furthermore, as a part of this overall project, Stantec is analyzing the effects of a potential breakout from the Santa Cruz River which will generate a discharge within the Lee Moore Wash channel in excess of what can be generated from the Lee Moore Wash basin. These details were discussed between JEF, Stantec, and PCRFCD with the conclusion being that modeling this area would add little useful information to the overall project at this time. Further analysis of the breakout may be of use if either it is found that the Santa Cruz River breakout is not as severe as originally concluded or if structural measures are employed upstream to contain the Santa Cruz River breakout flow.

10.3 Summary Map

Plate 2 is included to summarize the results of the FLO-2D modeling. This plate shows the 10- and 100-year flood limits along with some significant flow paths. In addition, the 10-, 25-, and 100-year peak discharge data have been summarized at several key points of interest.

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Appendix B - Northern Flow Splits Analyses

B Northern Flow Splits Analyses

Prior to the development of the extensive FLO-2D modeling discussed throughout the report, JEF prepared three flow split analyses for Stantec to assist with the HEC-HMS model development. The analyses were conducted while under contract with Stantec and were a part of Task B of Pima County contract number 16-59-S-138098-0606. The HEC-HMS models were developed by Stantec. Through the course of the watershed delineation, Stantec identified several areas where it was not readily clear as to which direction to route a hydrograph from a concentration point. JEF developed FLO-2D models in these areas with the purpose of defining which direction(s) to route hydrographs. The results of the FLO-2D modeling have already been shared with Stantec and incorporated within the HEC-HMS model. JEF also produced shapefiles representing the flooded area and shared these shapefiles with Stantec for use in the floodplain mapping. The FLO-2D methodology and results are included within this report for documentation and continuity purposes.

B.1 Modeling Methodology

The FLO-2D FRM, version 2006, was used to model flow splits.

- Terrain data was obtained from the Pima Association of Governments (PAG) in the form of Digital Elevation Model (DEM) data in text file format. The DEMs typically have ground data on an 8-foot grid. The FLO-2D Grid Developer System (GDS) was used to interpolate the elevation points.
- Hydrographs were obtained from Stantec and input into the models within the INFLOW.DAT file. In order to avoid over concentration of inflow, several of the hydrographs were evenly divided amongst multiple grid elements. A hydrograph divided amongst n grid elements had the discharge divided by n for each ordinate.
- Shapefiles were developed representing the Manning's roughness coefficient within the modeled area. The GDS was used to assign the roughness values based upon location of the grid in relation to the roughness shapefiles.
- The grid size varied between the models and was largely dependent upon the modeled area and discharge. An attempt was made to keep the number of grid elements below 15,000 to minimize computational time.
- Floodplain cross sections were encoded to record the peak discharge and hydrograph at various locations, but most importantly at the most downstream boundary of the model. Hydrographs from the HYCROSS.OUT file represent the flow split hydrographs.

B.2 Flow Split Locations and Extent

The location and extent of the 3 flow split models are shown on Figures B-1 and B-2 and on Plate 1. The models generally cover areas where flow travels west from an area of tributary to distributary flow patterns. The models are named for the concentration point, labeled by Stantec (in preliminary models, these may have changed since), which is upstream of the flow split. The J2 model is within the Franco Wash basin and documents the flow split between the Franco Wash to the north and a Franco Wash tributary to the south. The J4 model represents a split which occurs within the Franco Wash tributary, upstream of the J2 model. The north flow split drains to the Franco Wash tributary while the south split drains to a Flato Wash tributary within the J12 model area. The J12 model is the largest in regards to geographic area and represents flow splits between the Flato, Cuprite, and Petty Ranch Washes. The southern flow splits enter into the larger two-dimensional flow area discussed within the report.

Note that the more detailed, 100-foot grid models include this J12 flow split area with direct runoff on the surface computed with FLO-2D. The decision to do this followed preliminary analyses which determined that modeling the J12 split separate of the remainder of the FLO-2D model area artificially contained runoff to the north, runoff which splits into the Cuprite Wash.

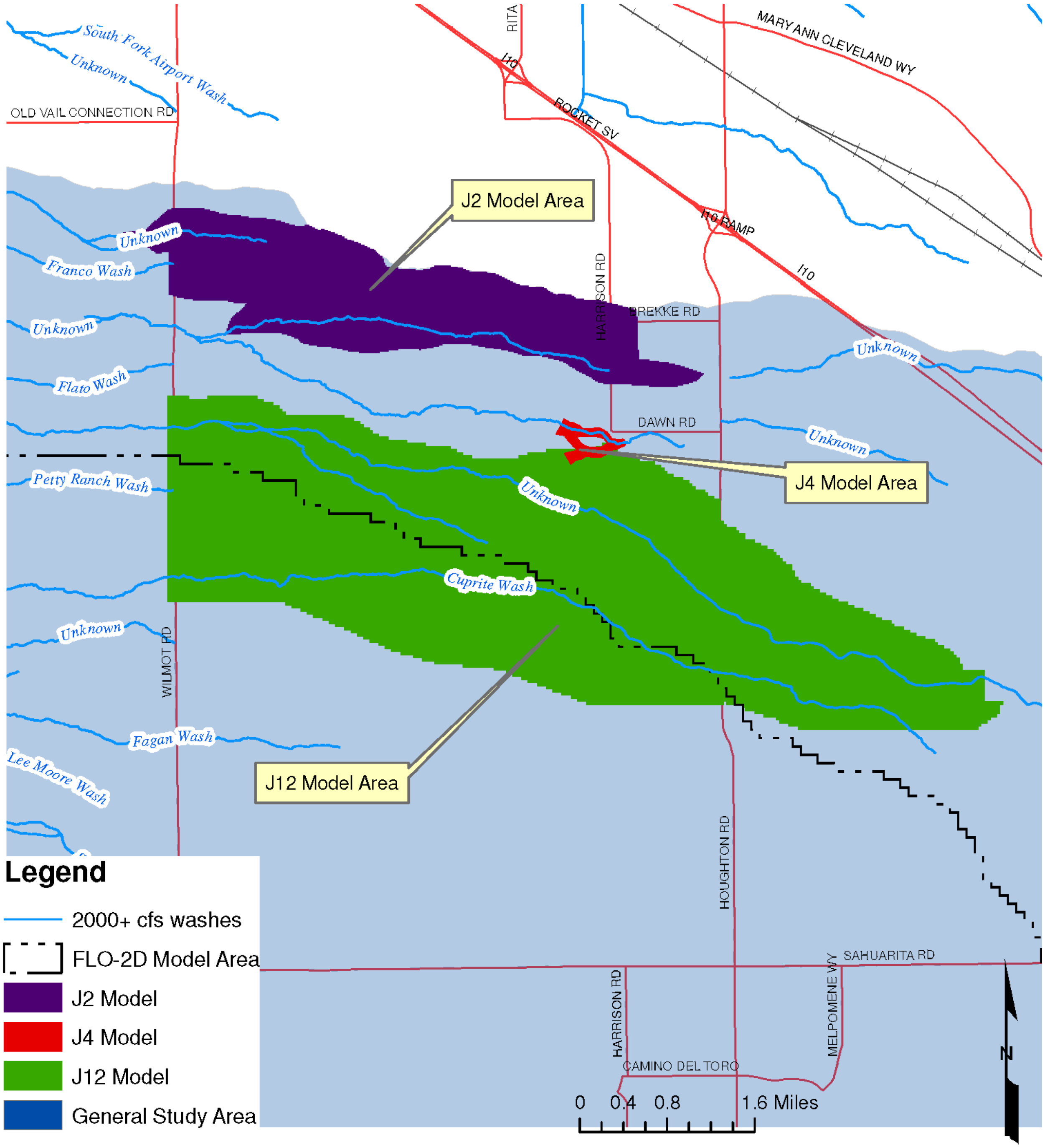

Figure B - 1 - Location map for northern flow split analyses

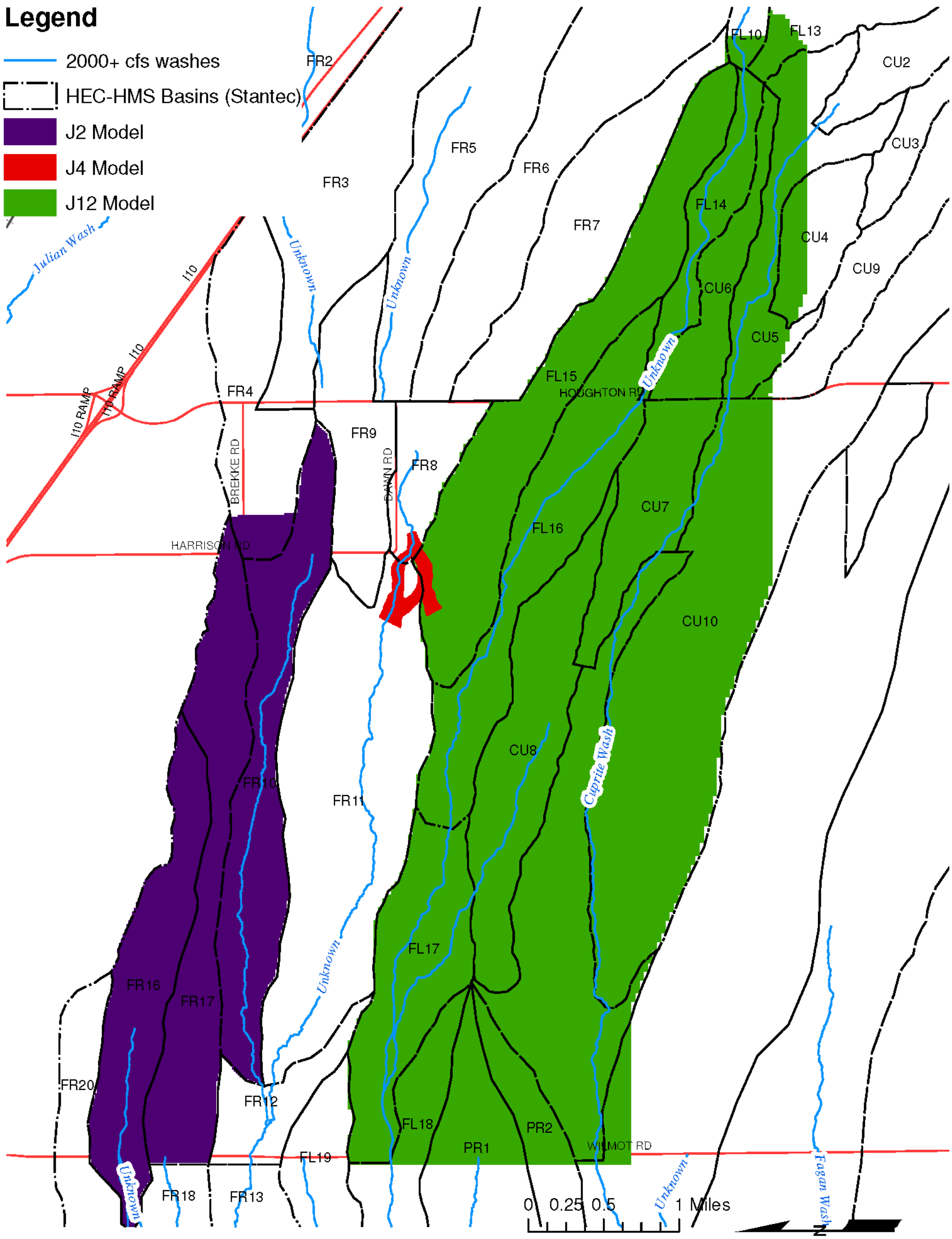

Figure B - 2 - Location map for northern flow split analyses with Stantec sub-basins

B.3 Results

The various flow split models are summarized in the following subsections in the order they were prepared. Further details can be found on Plate 1 which shows the flow depths, flow recording cross section locations, and inflow hydrograph locations. The FLO-2D input files, output files, and FLO-2D Mapper generated shapefiles are found within the attached digital files.

B.3.1 J4

Table B.1 – Summary of J4 Model

Grid element spacing (ft)	16	
Number of elements	11,839	
Inflow hydrograph peak discharge (cfs), 3-hr / 24-hr	1,601	1,280
Inflow hydrograph volume (ac-ft) , 3-hr / 24-hr	361	592
Outflow volume from grid (ac-ft) , 3-hr / 24-hr	356	586
Volume of floodplain storage (ac-ft) , 3-hr / 24-hr	5	6
Number of floodplain cross sections coded	6	
Number of flow splits recorded	2	
Flow split labels	J4-South, J4-North	

Table B.2 – Summary of J4 Flow Splits

Flow Split Label	Corresponding Cross Section	Sub-basin Split Drains Into	Q 3-hr (cfs)	Q 24-hr (cfs)	V 3-hr (ac-ft)	V 24-hr (ac-ft)
J4-South	CS 4	Near the outfall of FL15	359	229	48	37
J4-North	CS 5	Upland FR11	1,248	1,055	308	550

B.3.2 J2

Table B.3 – Summary of J2 Model

Grid element spacing (ft)	65	
Number of elements	24,215	
Inflow hydrograph peak discharge (cfs), 3-hr / 24-hr	3,230	2,710
Inflow hydrograph volume (ac-ft) , 3-hr / 24-hr	1,031	1,704
Outflow volume from grid (ac-ft) , 3-hr / 24-hr	886	146
Volume of floodplain storage (ac-ft) , 3-hr / 24-hr	145	1,558
Number of floodplain cross sections coded	11	
Number of flow splits recorded	3	
Flow split labels	J2-South, J2-Mid, J2-North	

Table B.4 – Summary of J2 Flow Splits

Flow Split Label	Corresponding Cross Section	Sub-basin Split Drains Into	Q 3-hr (cfs)	Q 24-hr (cfs)	V 3-hr (ac-ft)	V 24-hr (ac-ft)
J2-North	CS 1	Outfall of FR16	914	819	267	454
J2-Mid	CS 2	Outfall of FR17	642	609	230	424
J2-South	CS 4	Outfall of FR10	0	0	0	0

B.3.3 J12

Table B.5 – Summary of J12 Model

Grid element spacing (ft)	150
Number of elements	15,907
Inflow hydrograph peak discharge (cfs)	1,260
Inflow hydrograph volume (ac-ft)	4644.2
Outflow volume from grid (ac-ft)	3955.3
Volume of floodplain storage (ac-ft)	688.9
Number of floodplain cross sections coded	28
Number of flow splits recorded	5
Flow split labels	Cuprite, PR-S, PR-N, FL-S, FL-N

Table B.6 – Summary of J12 Flow Splits

Flow Split Label	Corresponding Cross Section	Sub-basin Split Drains Into	Q 24-hr (cfs)	V 24-hr (ac-ft)
Cuprite	CS 1	Outfall of Unlabeled Cuprite	2,383	1,519
PR-S	CS 2	Upland PR 2	1,372	987
PR-N	CS 3	Upland PR 1	42	30
FL-S	CS 4	Upland FL 18	132	100
FL-M	CS 5	Upland FL 17	899	826
FL-N	CS 6	Mid FL 17	707	504

Appendix C - Digital Files

Several shapefiles are included: 10-year flood limits, 100-year flood limits, flow recording cross sections, inflow locations, and outflow locations. While most are self explanatory, the flow recording cross sections shapefile fields are detailed in the following table.

Field	Example	Description
CS_LABEL	6-087	Cross section label, including model number and CS number from model
Q_PEAK	1,230	Maximum 100-year discharge based upon 100-yr, 3- and 24-hour models. 24-hour discharge shown in major flow corridors per "FORCE_24HR" field.
DEP_100	10.86	Maximum 100-year flow depth based upon 100-yr, 3- and 24-hour models. 24-hour depth shown in major flow corridors per "FORCE_24HR" field.
VEL_100	7.79	Maximum 100-year flow velocity based upon 100-yr, 3- and 24-hour models. 24-hour shown in major flow corridors per "FORCE_24HR" field.
REGULATORY	YES	Yes if "Q_PEAK" is 100 cfs or more.
Q_100_03	1222	Recorded peak discharge during 100-yr, 3-hour storm
RND_100_03	1230	"Q_100_03" rounded up.
Q_100_24	988	Recorded peak discharge during 100-yr, 24-hour storm
RND_100_24	990	"Q_100_24" rounded up.
TP_100_03	15.79	Recorded time of peak during 100-yr, 3-hour storm (rain starts at t=12)
TP_100_24	28.35	Recorded time of peak during 100-yr, 12-hour storm (rain starts at t=12)
VOL_100_03	609	Recorded runoff volume during 100-yr, 3-hour storm
VOL_100_24	964.14	Recorded runoff volume during 100-yr, 24-hour storm
Q_RATIO	1.24	Ratio of Q_{100-3} to Q_{100-24}
T_RATIO	0.56	Ratio of T_{100-3} to T_{100-25} (T=TP-12)
VOL_RATIO	0.63	Ratio of $Volume_{100-3}$ to $Volume_{100-26}$
DEP_100_03	10.86	100-yr, 3-hour flow depth obtained from analysis external of FLO-2D.
DEP_100_24	9.82	100-yr, 24-hour flow depth obtained from analysis external of FLO-2D.
VEL_100_03	7.79	100-yr, 3-hour flow velocity obtained from analysis external of FLO-2D.
VEL_100_24	7.04	100-yr, 24-hour flow velocity obtained from analysis external of FLO-2D.
Q_010	310	Recorded peak discharge during 10-yr, 3-hour storm
Q_025	488	Recorded peak discharge during 25-yr, 3-hour storm
TP_010	22.14	Recorded time of peak during 10-yr, 3-hour storm (rain starts at t=12)
TP_025	16.76	Recorded time of peak during 25-yr, 3-hour storm (rain starts at t=12)
VOL_010	254.24	Recorded runoff volume during 10-yr, 3-hour storm
VOL_025	377.59	Recorded runoff volume during 25-yr, 3-hour storm
MAXSTORM	3 Hour	Details which discharge, Q_{100-3} or Q_{100-24}, is greater
FORCE_24HR	NO	Describes whether the 100-yr, 24-hour peak discharge is forced to show
SHOW	YES	Describes whether the cross section is shown on the flood maps
FLO_DIR	4	Direction flow recorded, 1=N, 2=E, 3=S, 4=W, 5=NE, 6=SE, 7=SW, 8=NW

Appendix D - Large-Scale FLO-2D Model Discussion

D Large-Scale Model

This section discusses the development of and results from the large-scale (lower grid resolution) FLO-2D model. The model is generally south of the Flato Wash. The results of this model were used to develop the ultimate, more detailed models. Because the more detailed models discussed within this report supersede the large-scale models, the large-scale model input and output is omitted from this report to avoid confusion.

D.1 Elevation Data

Elevation data used in the large-scale model was obtained from United States Geological Survey (USGS) Digital Elevation Model (DEM) data. DEM data on a 10 meter grid was obtained for the nine 1:24,000 scale quadrangle maps covering the model area. USGS DEM data was used instead of PAG DEM/DTM data for the following reasons:

- The PAG data does not cover the entire study area.
- A single square mile of DEM data from PAG contains approximately 500,000 elevation points, requiring extensive computational resources over the entire 126 square mile model area.
- The resolution of the FLO-2D model is coarse; 8-foot PAG DEM data would not be necessary on grids exceed exceeding 3 acres in size.

FLO-2D GDS can import the DEM data directly, but the horizontal projection of the DEM data does not match the state plane projection used by Pima County. Furthermore, the DEM data contains metric elevation points. For these reasons, the DEM files were projected with ArcView software and the elevation points were scaled appropriately before importing into the GDS. The resulting elevation points are on the state plane coordinate system with elevations in feet.

D.2 Grid Development

The FLO-2D GDS was used to develop the grid. Along the north and east side of the model area, the grid was cut to align with the watershed delineated by Stantec for the Cuprite and Flato basins. The grid was limited along the south and the west by an apparent watershed divide. The most downstream limit of the FLO-2D model grid is the east side of Old Nogales Highway, where the Lee Moore Wash crosses under the railroad bridge. This location was assigned as outflow from the model. Additional outflow was assigned along Sahuarita Road, west of the Gunnery Range Wash, where a flow split upstream of this location causes a sizeable volume of water to exit the basin.

Along the west side of the study area, north of Sahuarita Road, there currently exist berms that contains runoff to the basin. These berms are visible on the PAG topography but not on the USGS DEM. An analysis performed entirely on USGS data would likely not account for these berms and flow would not be contained to the basin. Therefore, the grid has been defined in this area based on PAG topographic data. Grid element elevations in this area have been adjusted manually to provide positive drainage in the downstream direction. It should be noted that the western edge of the model does not accurately model the hydraulics.

The grid element size used in initial modeling is 400 feet, requiring approximately 22,000 grid elements for the model area and approximately one hour of run time. The final model is a 200-foot grid model with almost 90,000 grid elements and a substantially longer run time. The 400-

foot grid model is used in calibration routines and to determine general trends before fully developing the 200-foot grid model.

The GDS was used to import the DEM data and interpolate elevation points. Some grid elements required manual adjustment of elevation, specifically in the highest elevations with significant relief within a single grid element and/or where incised flow paths run diagonal to the orthogonal grid system. Grid element elevations were adjusted to provide positive relief in the downstream direction and to avoid ponding of runoff during the simulation.

The FLO-2D model was developed with floodplain data only, no channels were specifically modeled. Attempts were made to model some of the larger watercourses within the incised, downstream areas. However, the course resolution of the model did not couple well with the detail associated with modeling the channels. Furthermore, detailed modeling within these incised areas (and the additional effort required to do so) is better left to the more detailed models based upon the PAG elevation data.

D.3 Inflow From J-12 Model

Three hydrographs were added to this model as inflow from the J-12 flow split model. The hydrographs from J12 cross sections 1, 2, and 3 were input into the plan position within this model relative to their placement within the J12 model.

D.4 Precipitation

The 100-year, 24-hour storm was modeled following the SCS Type I distribution with a single rainfall depth of 4.37 inches.

Appendix E - FLO-2D Calibration to HEC-HMS

E.1 HEC-HMS Calibration Models

The HEC-HMS parameters are summarized in Table E - 1. Note that some of the parameters differ from the HEC-HMS model submitted for this project for comparative purposes. The CN has been rounded and impervious area has been set to 0 in the HEC-HMS model to isolate this variable.

Table E - 1 – Summary of HEC-HMS Input Parameters

Sub-basin	Area (sq mi)	CN	Rainfall Depth (in)	Q-100, 24-hour (cfs)	q (cfs/sq-mi)	Time of Peak[1] (hr)
PR1	2.809	84	4.15	626	223	24.5
PR2	1.479	84	4.15	326	220	24.6
PR3	1.100	87	4.15	334	304	24.7
Combined PR	**5.388**	**84.6**	**4.15**	**1,134**	**210**	**24.9**
CU1	0.654	87	4.37	395	604	22.5
CU2	0.814	83	4.37	377	463	22.7
Combined CU	**1.468**	**84.8**	**4.37**	**594**	**405**	**23.0**
FR6	2.124	88	4.30	762	359	23.5
FR7	1.163	88	4.30	438	377	23.4
FR8	0.410	88	4.30	174	424	23.1
Combined FR	**3.697**	**88**	**4.30**	**1,258**	**340**	**24.1**

Note 1 – Rainfall begins at hour 12.0

E.2 Calibration Model Results

The following are observations regarding the use of the depth varied roughness equation.

- For most models with the DVR turned on, the time of peak increases as the floodplain roughness increases. When the DVR is turned off, this relationship is not consistent and sometimes a decreasing time of peak is associated with an increasing floodplain roughness.
- Turning the DVR off almost always causes the model to predict a greater discharge and a shorter time of peak.
- The curve of floodplain roughness versus predicted peak discharge is more uniform when the DVR is turned on.

<u>Based on the observations, it is recommended to use the depth varied roughness equation as it generates more consistent results.</u>

The following are observations regarding the effects of grid size.

- For both the Petty Ranch and Franco models, the predicted peak discharge increases with increased grid size when the lowest floodplain roughness coefficients (<0.030) are used.
- For both of the models, the use of a larger grid size will cause the model to predict a reduced peak discharge for floodplain roughness values of 0.030 to 0.040.

- For the Petty Ranch model, a larger grid size caused a greater time of peak prediction with the lower floodplain roughness values. Higher floodplain roughness values caused the model to predict a shorter time of peak for a larger grid size.
- For the Franco model, increasing grid size increased the time of peak for all models.

Increasing the grid element size may change the flow path length and/or path. A model with smaller grid elements can more accurately model attenuation on floodplain areas along with allowing flow to pass quicker in primary flow paths. A larger grid element size may have a similar effect as increasing the roughness coefficient. Based on these observations, it is recommended to consider a lower floodplain roughness value with larger grid size. For models with a larger grid size (200 feet or more), a floodplain roughness of 0.030 may be more appropriate than 0.040. These observations further justify using the smallest grid size within reason as larger grids generated reduced peak discharges.

The most consistent and predictable calibration was found in altering the floodplain roughness value.

- In general, the lower the floodplain roughness value, the greater the predicted peak discharge. When the value of floodplain roughness is set to 0.010, the model predicts a peak discharge of approximately 3 times the value predicted by HEC-HMS.
- Floodplain roughness values of 0.030 and 0.035 tended to generate the most consistent results. A value of 0.030 generated a peak discharge most in line with the HEC-HMS value.
- Floodplain roughness values of 0.040 generated less consistent results and many times generated a peak discharge substantially less than the HEC-HMS peak discharge.

Based on these results and the grid size discussion, a floodplain roughness value of 0.030 to 0.035 may be most appropriate. While this may seem low for a floodplain roughness value, it must be pointed out that the shallow roughness value is used for flow depths below 0.5 feet and then the depth varied roughness causes a smooth transition to the floodplain roughness value which is applicable to depths of greater than 3 feet. The vast majority of the floodplain will have flow depths much less than 3 feet and therefore generally remain within the shallow flow region.

The effects of the shallow roughness coefficient are not entirely consistent.

- In general, the lower the shallow roughness coefficient, the greater the predicted peak discharge. This was not always the case when the floodplain roughness was set to less than 0.030 but was generally the case for higher floodplain roughness values.
- The most consistent results tend to appear when the floodplain roughness is set to 0.030 or 0.035 and the shallow roughness is less than 0.20.
- The use of a shallow roughness coefficient of 0.25 generated inconsistent results.

The use of a shallow roughness coefficient of 0.10 and floodplain roughness coefficients of 0.030 or 0.035 generates the closest results to the HEC-HMS model.

The following figures and tables summarize the FLO-2D models. Note that the time of peak values reference models with rainfall beginning at hour 12.

Table E - 2– Input Summary for Model PR-1

Grid size (ft)	85	Shallow n	0.10
Number of grid elements	20,800	Limiting Froude #	0.85
Number of outflow grid elements	10	Model Label	PR-1
Modeled area (sq mi) w/o outflow	5.388		

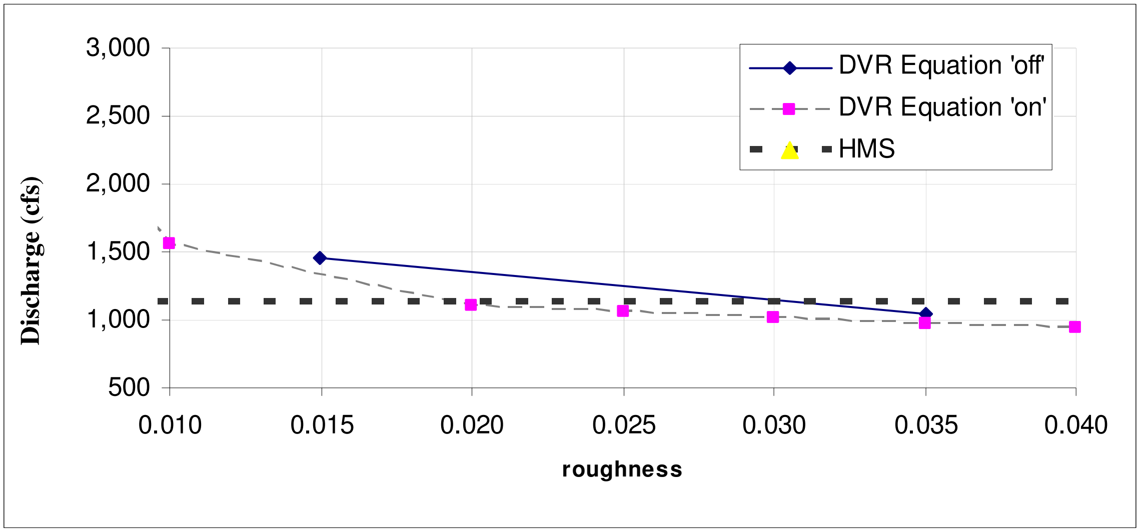

Figure E - 1 – Comparison of floodplain roughness to predicted peak discharge for Model PR-1

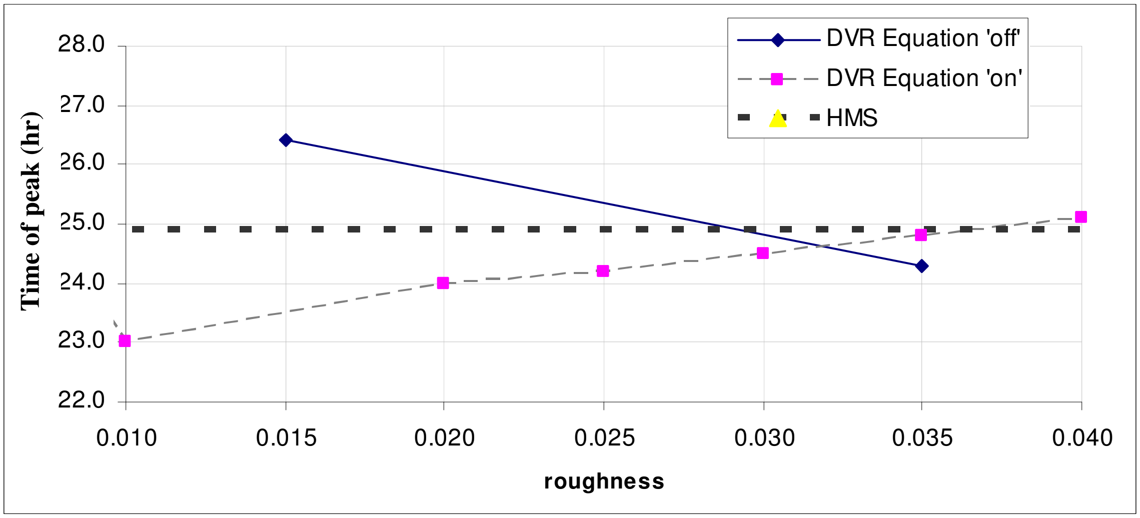

Figure E - 2 – Comparison of floodplain roughness to predicted time of peak for model PR-1

Table E - 3– Input Summary for Model PR-2

Grid size (ft)	200	Shallow n	0.10
Number of grid elements	3,762	Limiting Froude #	0.85
Number of outflow grid elements	7	Model Label	PR-2
Modeled area (sq mi) w/o outflow	5.388		

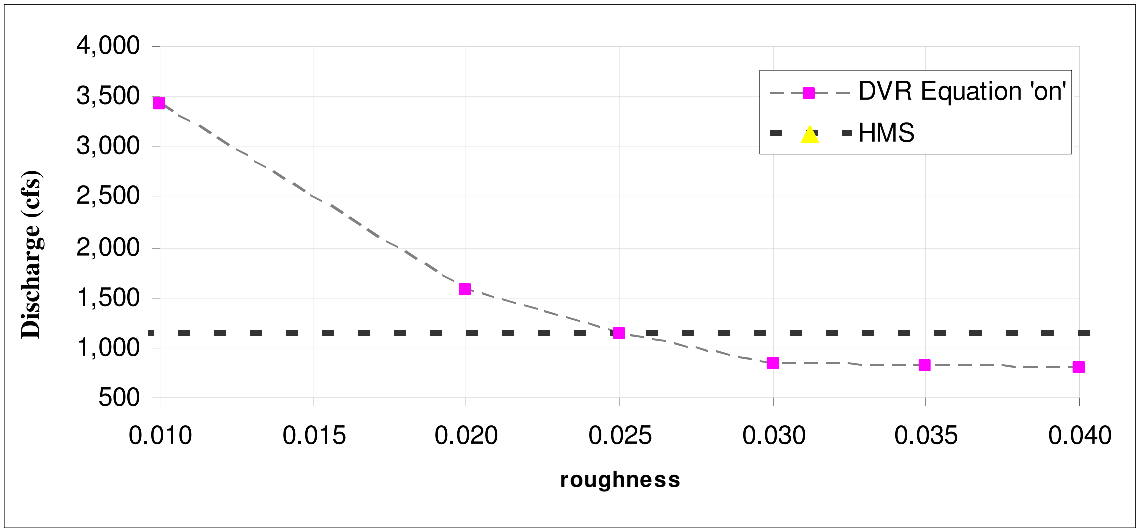

Figure E - 3 – Comparison of floodplain roughness to predicted peak discharge for Model PR-2

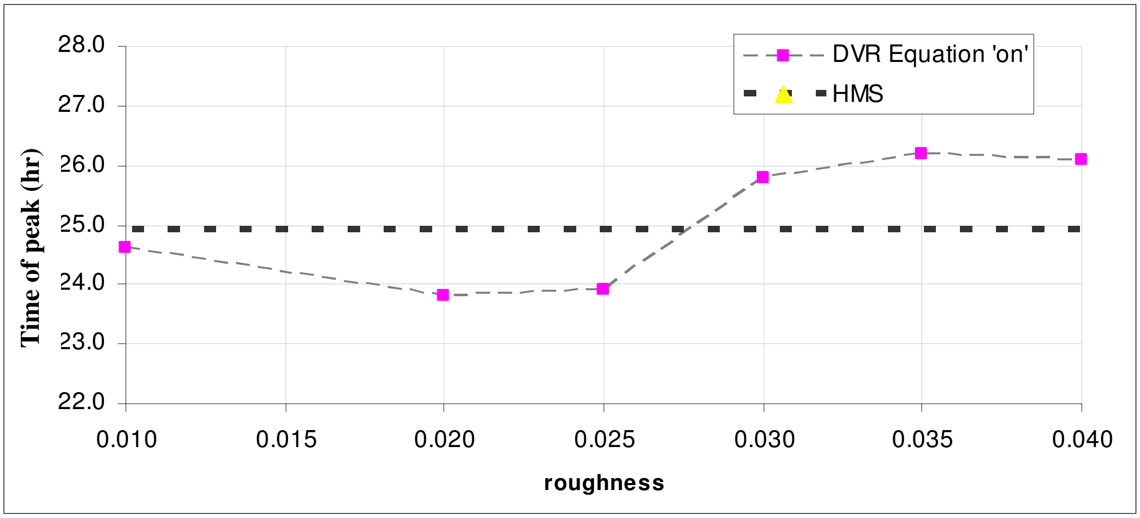

Figure E - 4 – Comparison of floodplain roughness to predicted time of peak for model PR-2

Table E - 4– Input Summary for Model PR-3

Grid size (ft)	200	Shallow n	0.15
Number of grid elements	3,762	Limiting Froude #	0.85
Number of outflow grid elements	7	Model Label	PR-3
Modeled area (sq mi) w/o outflow	5.388		

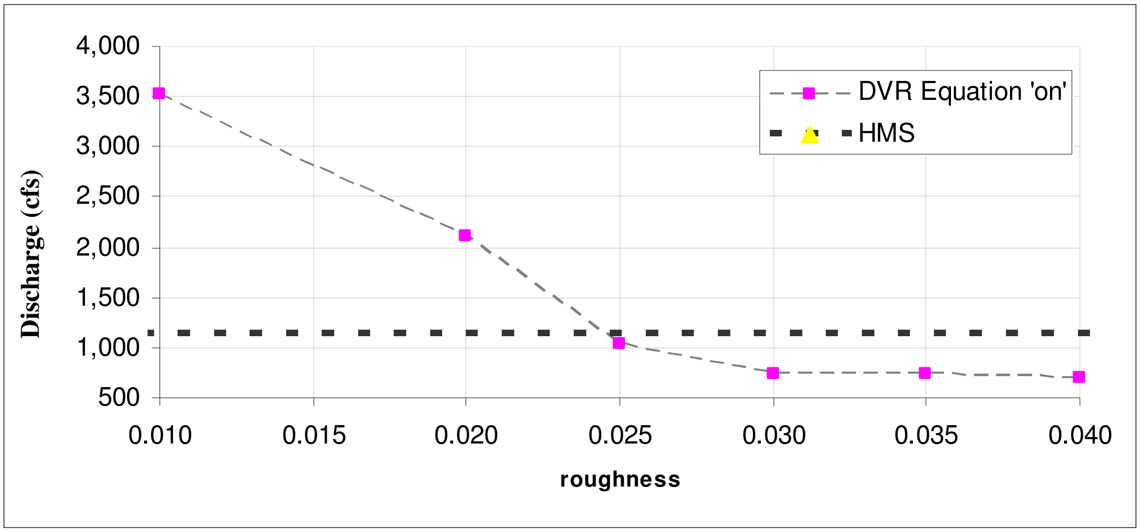

Figure E - 5 – Comparison of floodplain roughness to predicted peak discharge for Model PR-3

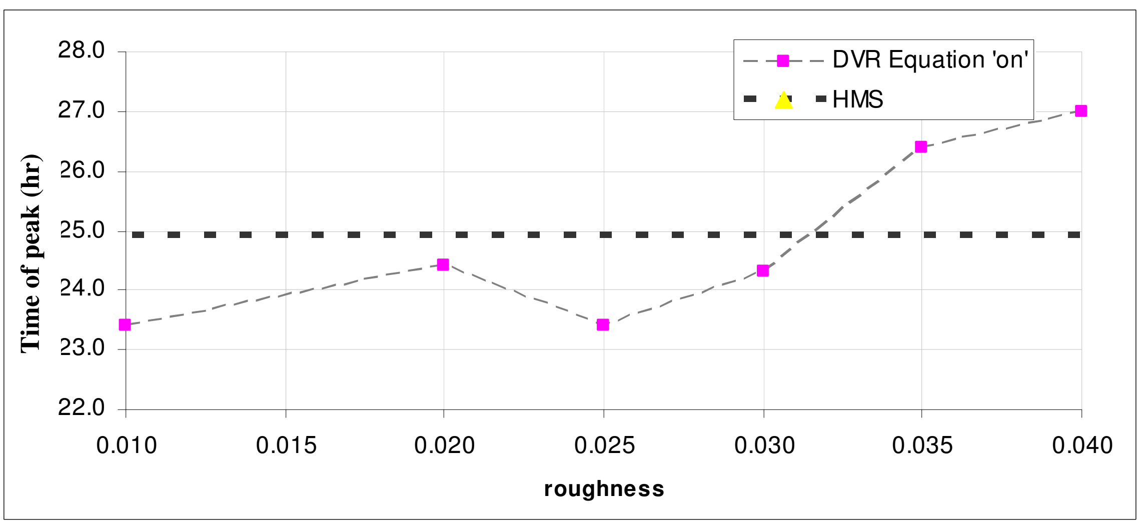

Figure E - 6 – Comparison of floodplain roughness to predicted time of peak for model PR-3

Table E - 5– Input Summary for Model PR-4

Grid size (ft)	200	Shallow n	0.20
Number of grid elements	3,762	Limiting Froude #	0.85
Number of outflow grid elements	7	Model Label	PR-4
Modeled area (sq mi) w/o outflow	5.388		

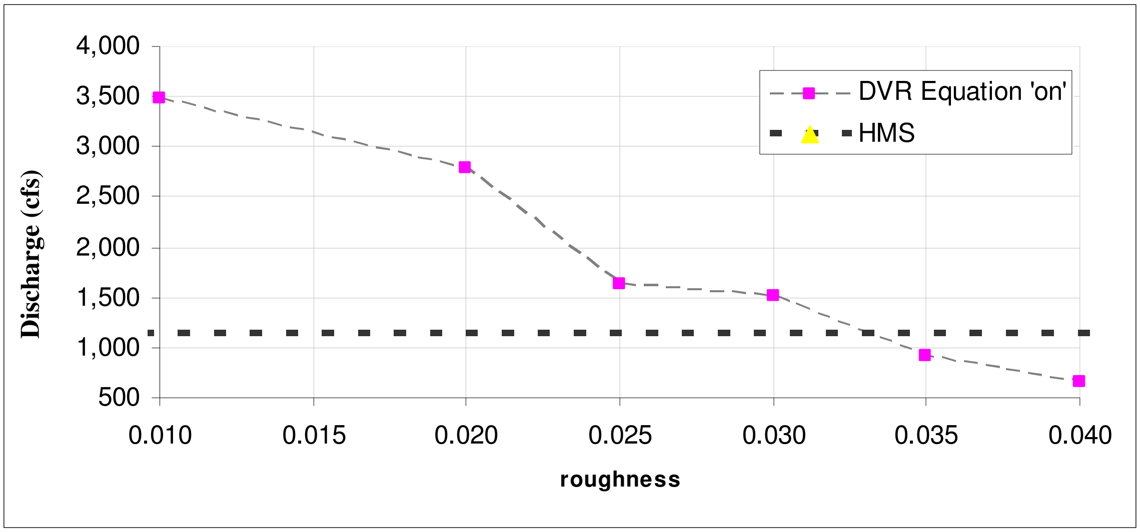

Figure E - 7 – Comparison of floodplain roughness to predicted peak discharge for Model PR-4

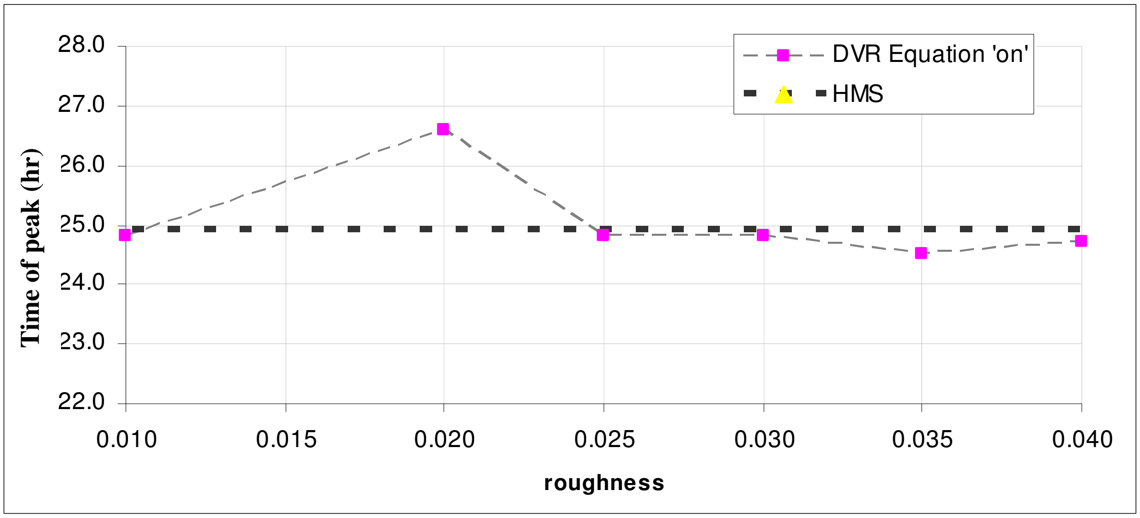

Figure E - 8 – Comparison of floodplain roughness to predicted time of peak for model PR-4

Table E - 6– Input Summary for Model PR-5

Grid size (ft)	200	Shallow n	0.25
Number of grid elements	3,762	Limiting Froude #	0.85
Number of outflow grid elements	7	Model Label	PR-5
Modeled area (sq mi) w/o outflow	5.388		

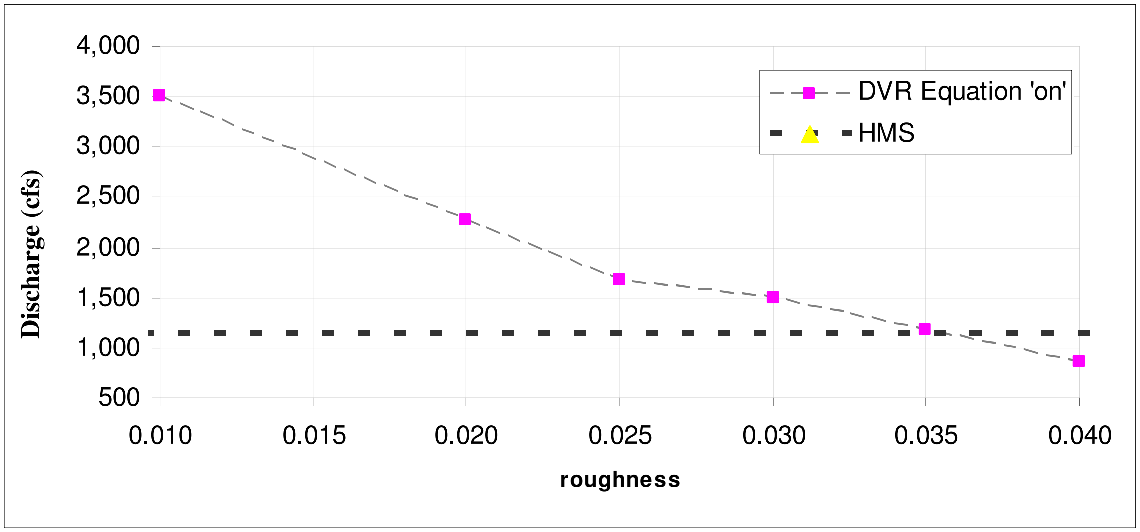

Figure E - 9 – Comparison of floodplain roughness to predicted peak discharge for Model PR-5

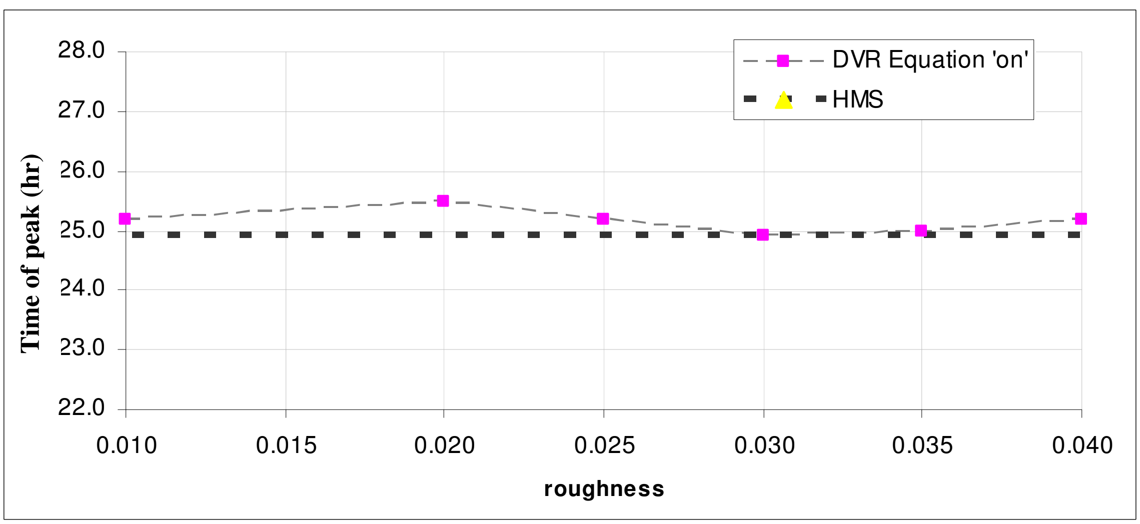

Figure E - 10 – Comparison of floodplain roughness to predicted time of peak for model PR-5

Table E - 7– Input Summary for Model CU-1

Grid size (ft)	85	Shallow n	0.10
Number of grid elements	5,664	Limiting Froude #	0.85
Number of outflow grid elements	5	Model Label	CU-1
Modeled area (sq mi) w/o outflow	1.467		

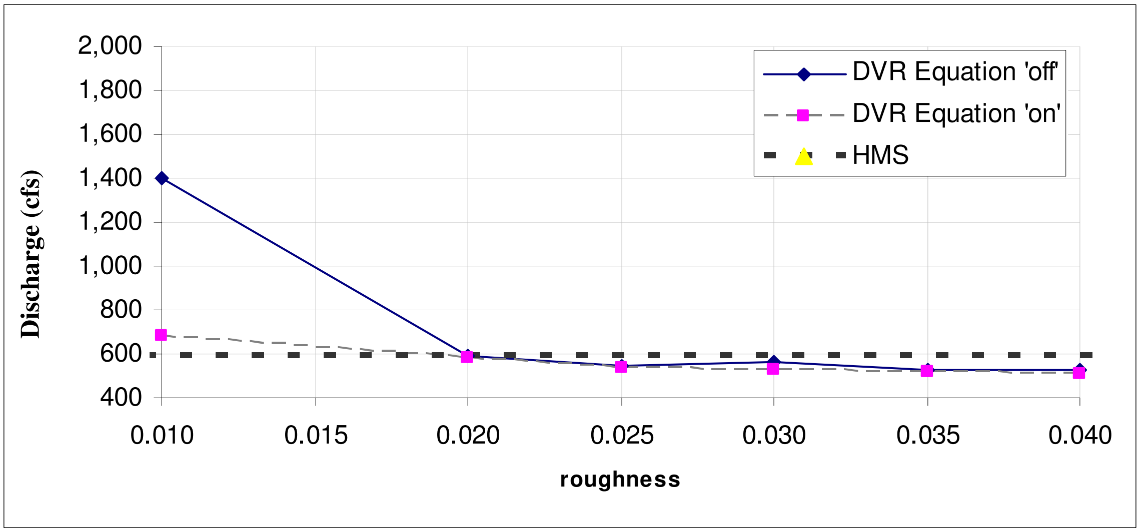

Figure E - 11 – Comparison of floodplain roughness to predicted peak discharge for Model CU-1

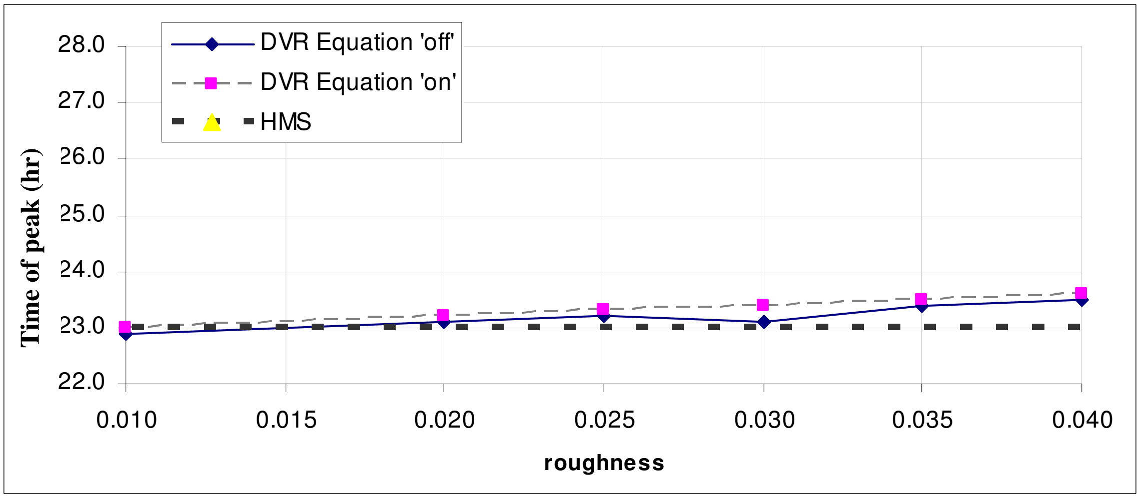

Figure E - 12 – Comparison of floodplain roughness to predicted time of peak for model CU-1

Table E - 8– Input Summary for Model CU-2

Grid size (ft)	85	Shallow n	0.15
Number of grid elements	5,664	Limiting Froude #	0.85
Number of outflow grid elements	5	Model Label	CU-2
Modeled area (sq mi) w/o outflow	1.467		

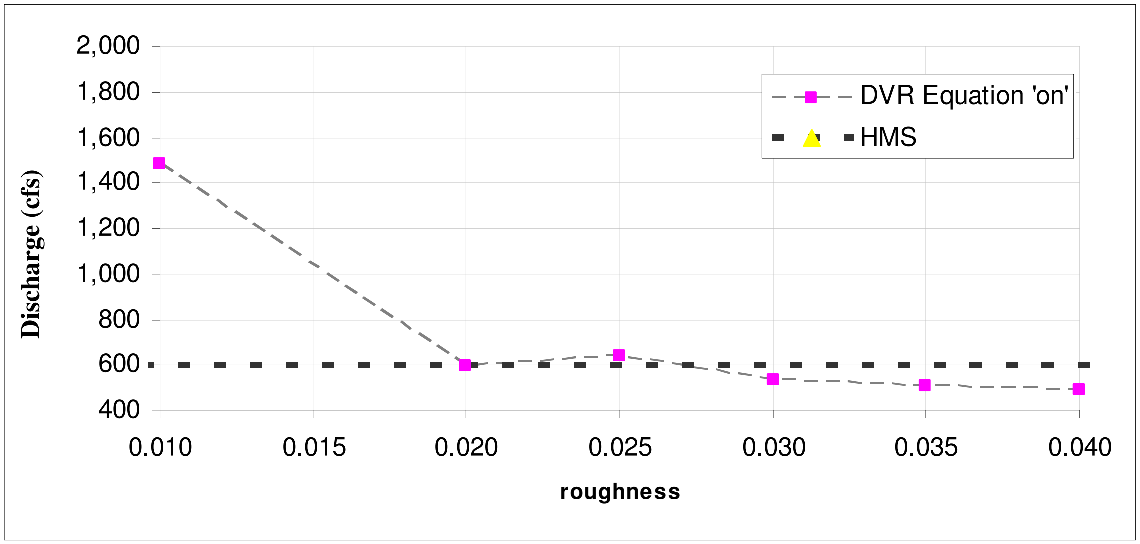

Figure E - 13 – Comparison of floodplain roughness to predicted peak discharge for Model CU-2

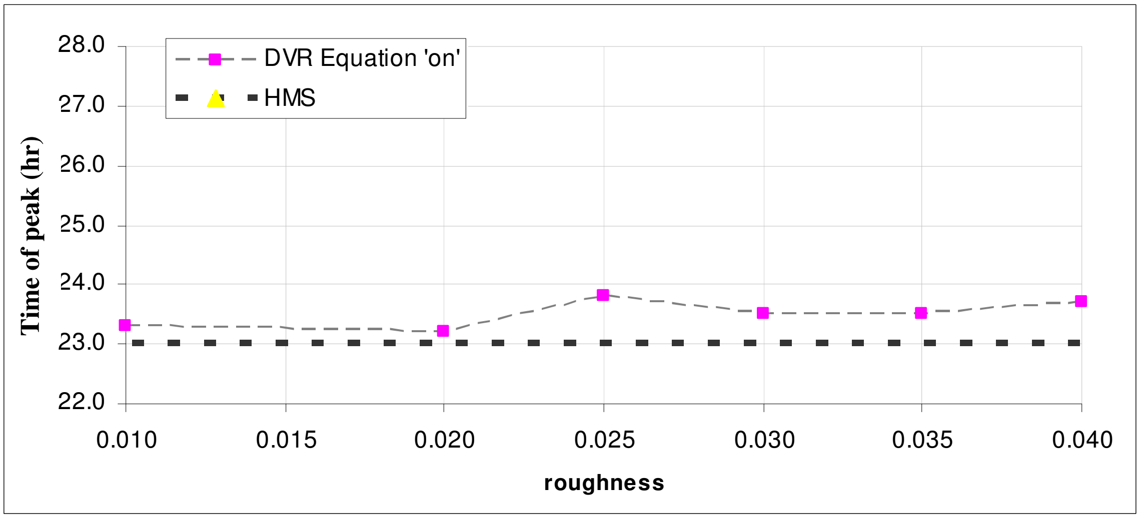

Figure E - 14 – Comparison of floodplain roughness to predicted time of peak for model CU-2

Table E - 9– Input Summary for Model CU-3

Grid size (ft)	85	Shallow n	0.20
Number of grid elements	5,664	Limiting Froude #	0.85
Number of outflow grid elements	5	Model Label	CU-3
Modeled area (sq mi) w/o outflow	1.467		

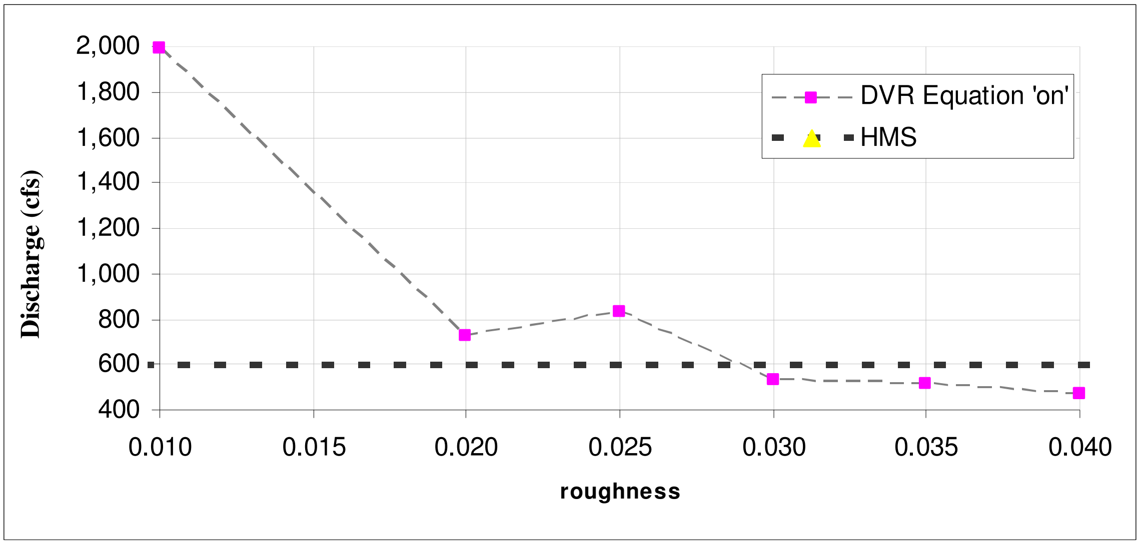

Figure E - 15 – Comparison of floodplain roughness to predicted peak discharge for Model CU-3

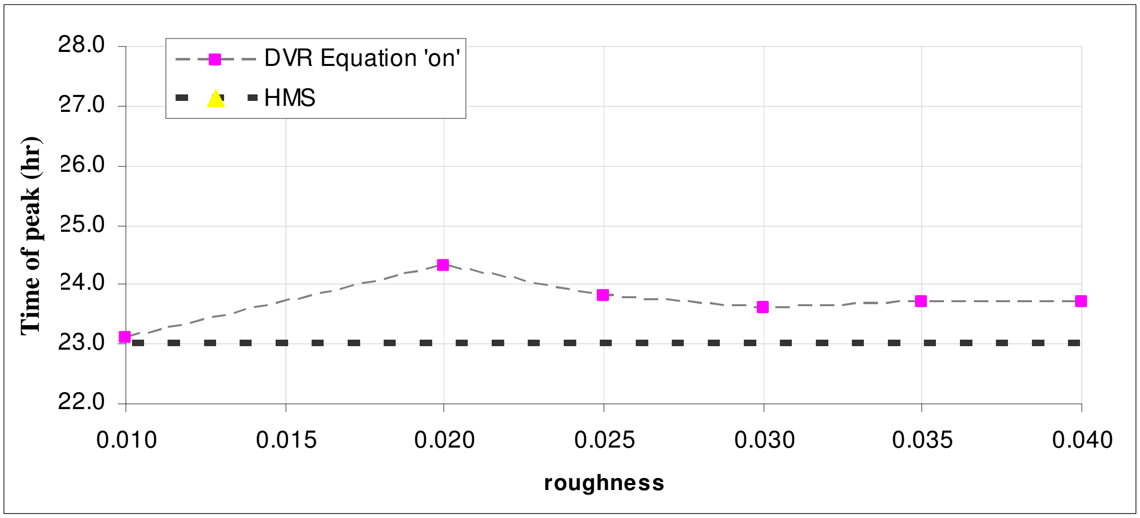

Figure E - 16 – Comparison of floodplain roughness to predicted time of peak for model CU-3

Table E - 10– Input Summary for Model CU-4

Grid size (ft)	85	Shallow n	0.25
Number of grid elements	5,664	Limiting Froude #	0.85
Number of outflow grid elements	5	Model Label	CU-4
Modeled area (sq mi) w/o outflow	1.467		

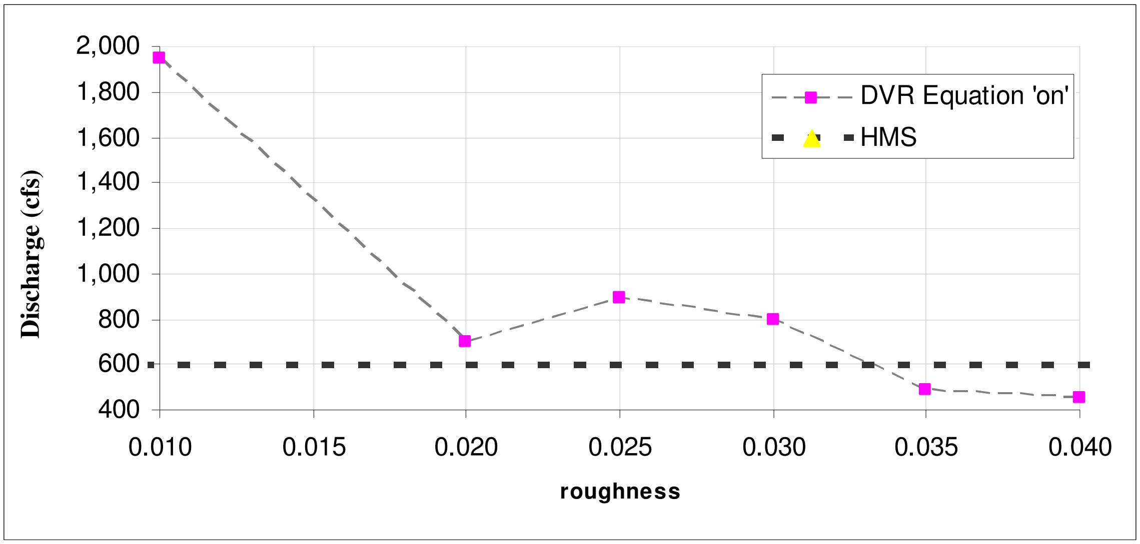

Figure E - 17 – Comparison of floodplain roughness to predicted peak discharge for Model CU-4

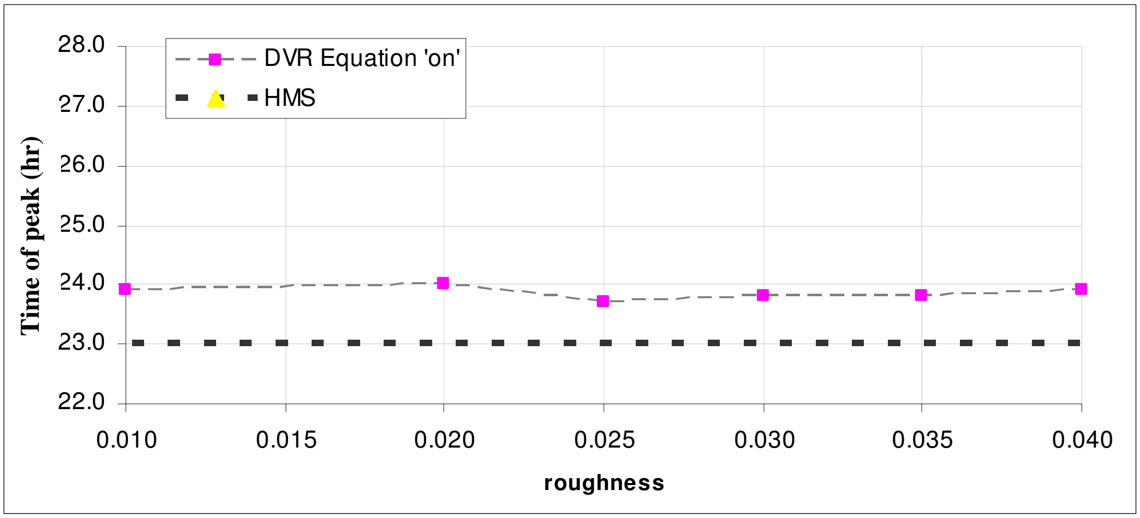

Figure E - 18 – Comparison of floodplain roughness to predicted time of peak for model CU-4

Table E - 11– Input Summary for Model FR-1

Grid size (ft)	85	Shallow n	0.10
Number of grid elements	14,278	Limiting Froude #	0.85
Number of outflow grid elements	5	Model Label	FR-1
Modeled area (sq mi) w/o outflow	3.699		

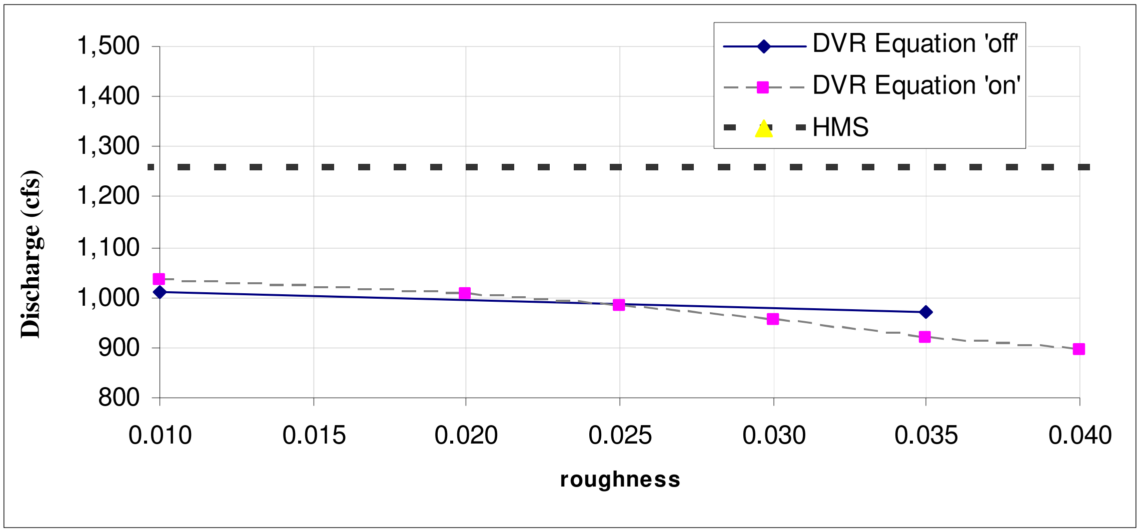

Figure E - 19 – Comparison of floodplain roughness to predicted peak discharge for Model FR-1

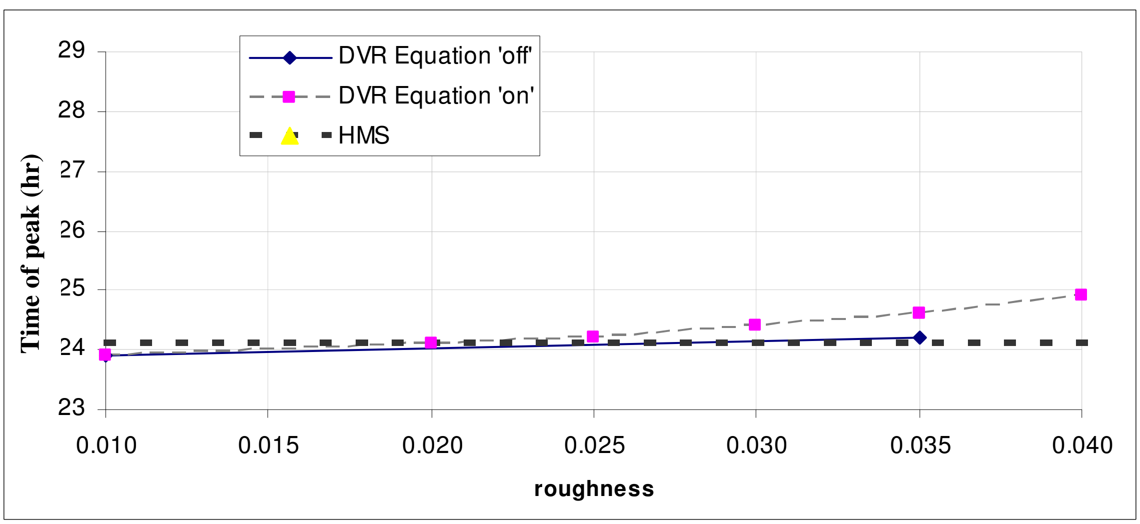

Figure E - 20 – Comparison of floodplain roughness to predicted time of peak for model FR-1

Table E - 12– Input Summary for Model FR-2

Grid size (ft)	200	Shallow n	0.10
Number of grid elements	2,580	Limiting Froude #	0.85
Number of outflow grid elements	3	Model Label	FR-2
Modeled area (sq mi) w/o outflow	3.697		

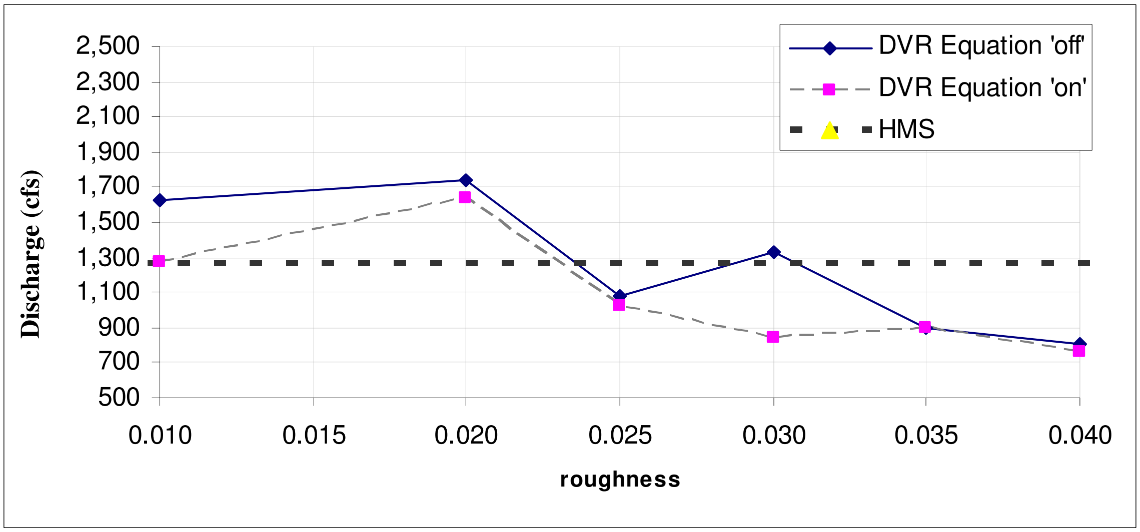

Figure E - 21 – Comparison of floodplain roughness to predicted peak discharge for Model FR-2

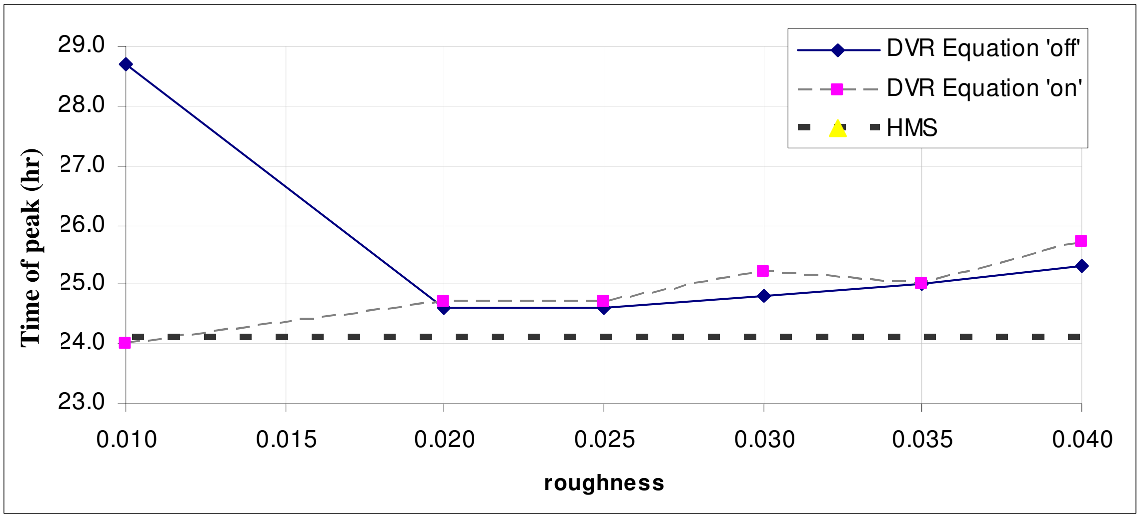

Figure E - 22 – Comparison of floodplain roughness to predicted time of peak for model FR-2

Table E - 13– Input Summary for Model FR-3

Grid size (ft)	200	Shallow n	0.15
Number of grid elements	2,580	Limiting Froude #	0.85
Number of outflow grid elements	3	Model Label	FR-3
Modeled area (sq mi) w/o outflow	3.697		

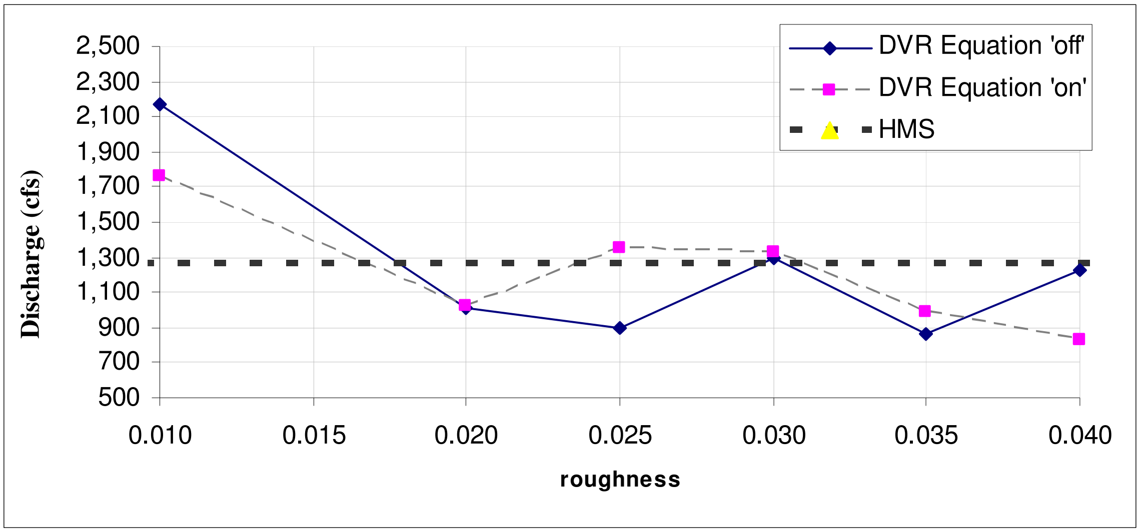

Figure E - 23 – Comparison of floodplain roughness to predicted peak discharge for Model FR-3

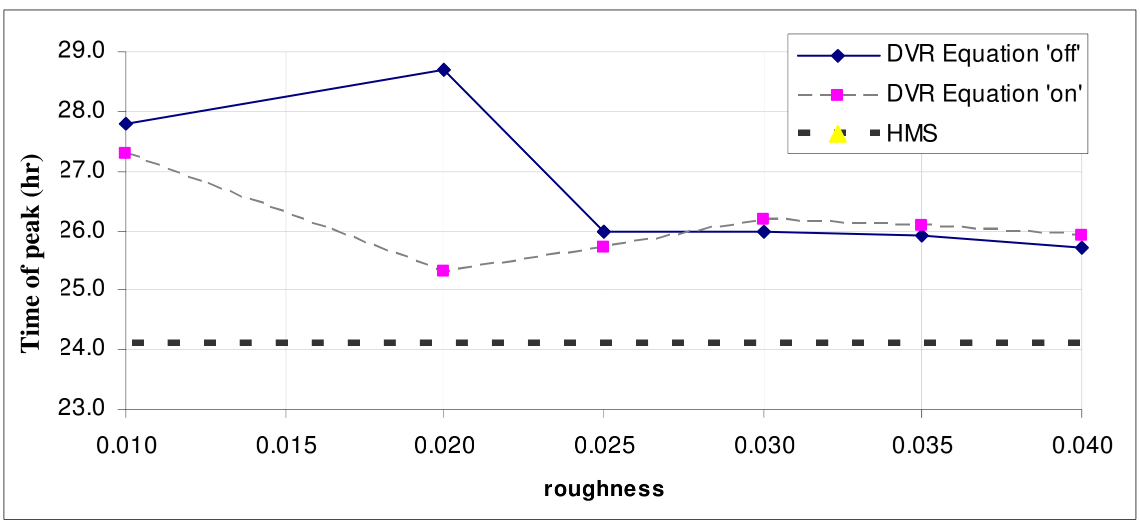

Figure E - 24 – Comparison of floodplain roughness to predicted time of peak for model FR-3

Table E - 14– Input Summary for Model FR-4

Grid size (ft)	200	Shallow n	0.20
Number of grid elements	2,580	Limiting Froude #	0.85
Number of outflow grid elements	3	Model Label	FR-4
Modeled area (sq mi) w/o outflow	3.697		

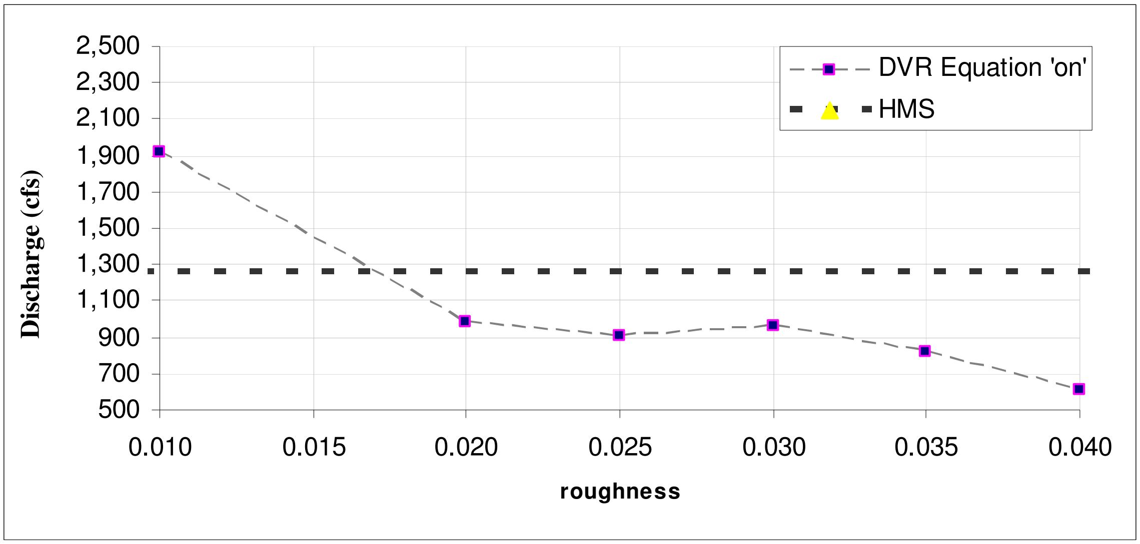

Figure E - 25 – Comparison of floodplain roughness to predicted peak discharge for Model FR-4

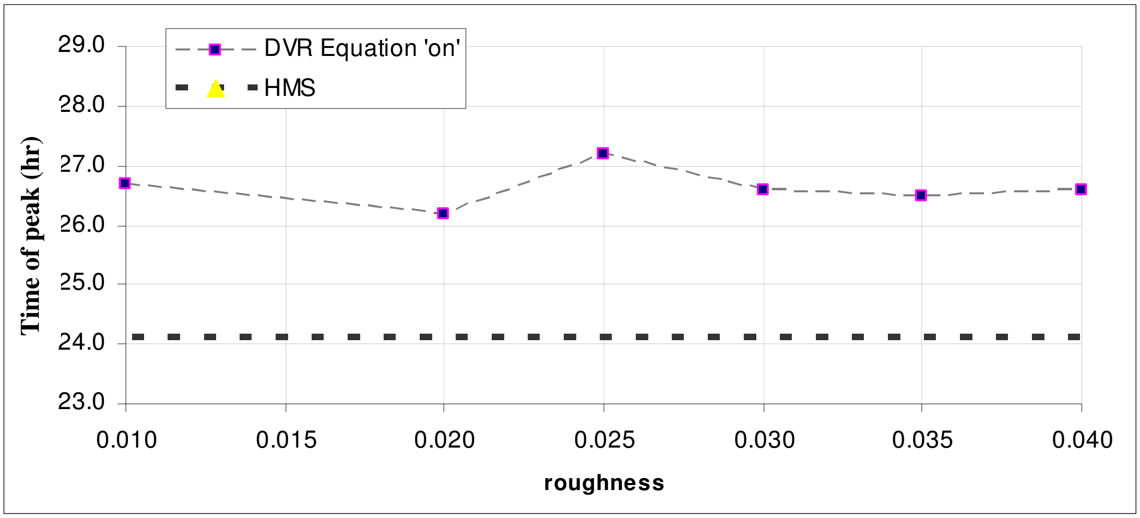

Figure E - 26 – Comparison of floodplain roughness to predicted time of peak for model FR-4

Table E - 15– Input Summary for Model FR-5

Grid size (ft)	200	Shallow n	0.25
Number of grid elements	2,580	Limiting Froude #	0.85
Number of outflow grid elements	3	Model Label	FR-5
Modeled area (sq mi) w/o outflow	3.697		

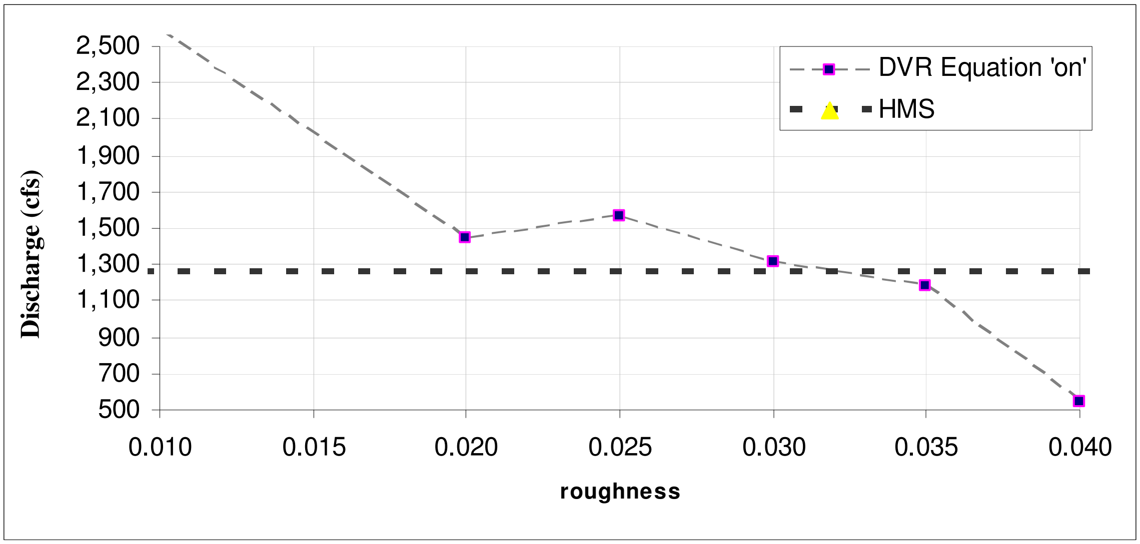

Figure E - 27 – Comparison of floodplain roughness to predicted peak discharge for Model FR-5

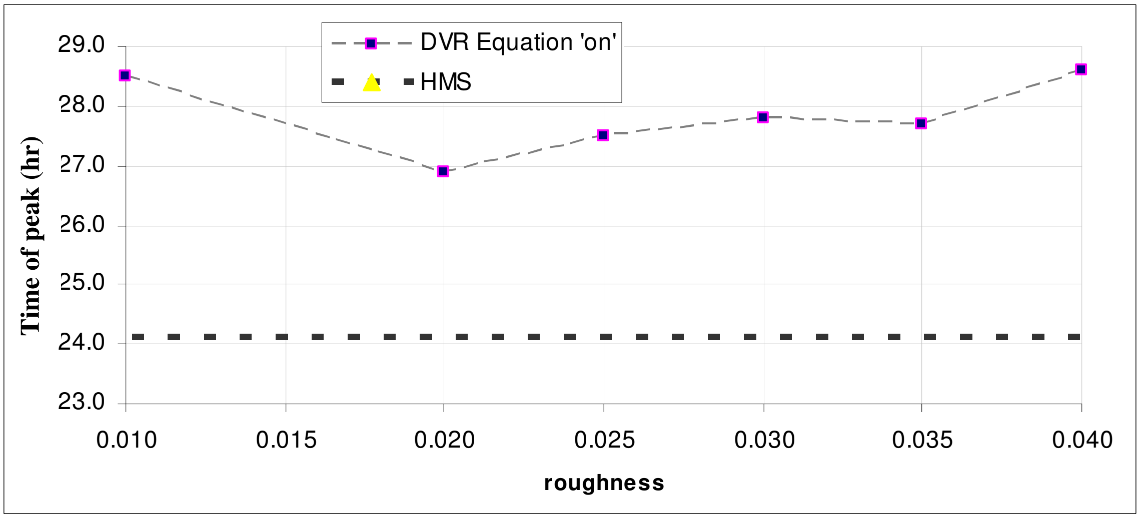

Figure E - 28 – Comparison of floodplain roughness to predicted time of peak for model FR-5

The results from the individual models have been combined to show the effects of changing the shallow flow roughness value and the grid size. The following figures compare the predicted peak discharge and time of peak to the applied shallow roughness coefficients for floodplain roughness values of 0.020 and greater. These comparisons only include those models with the depth varied roughness turned on.

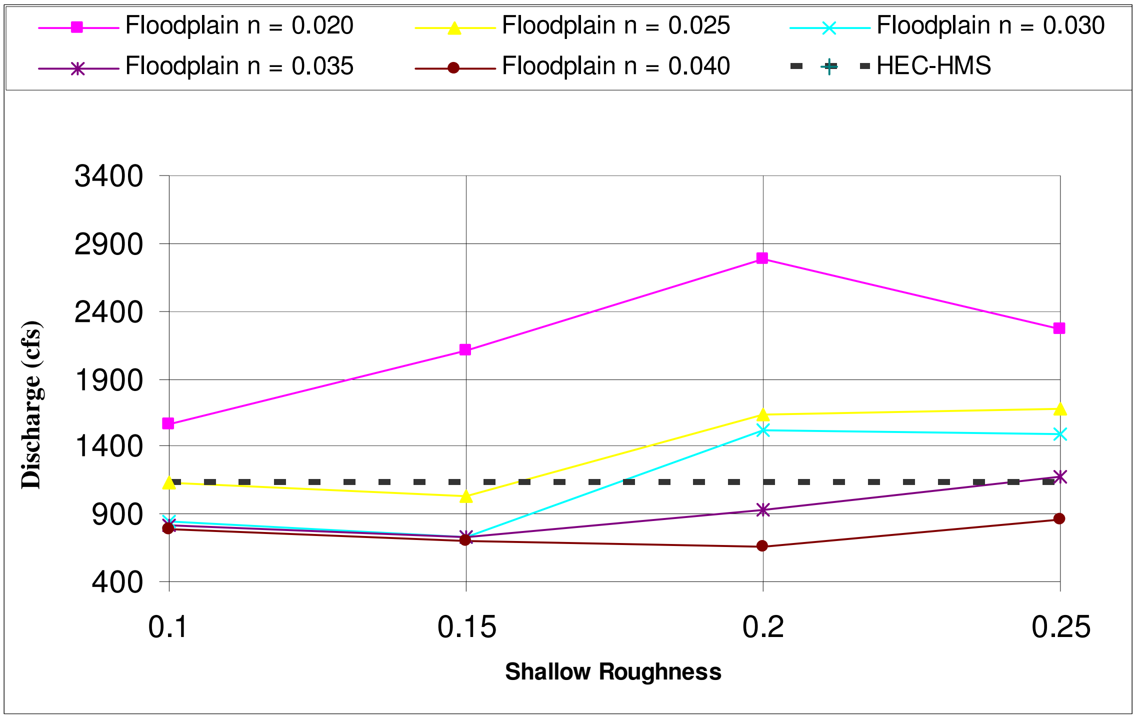

Figure E - 29 – Comparison of shallow roughness to predicted peak discharge for Petty Ranch Models

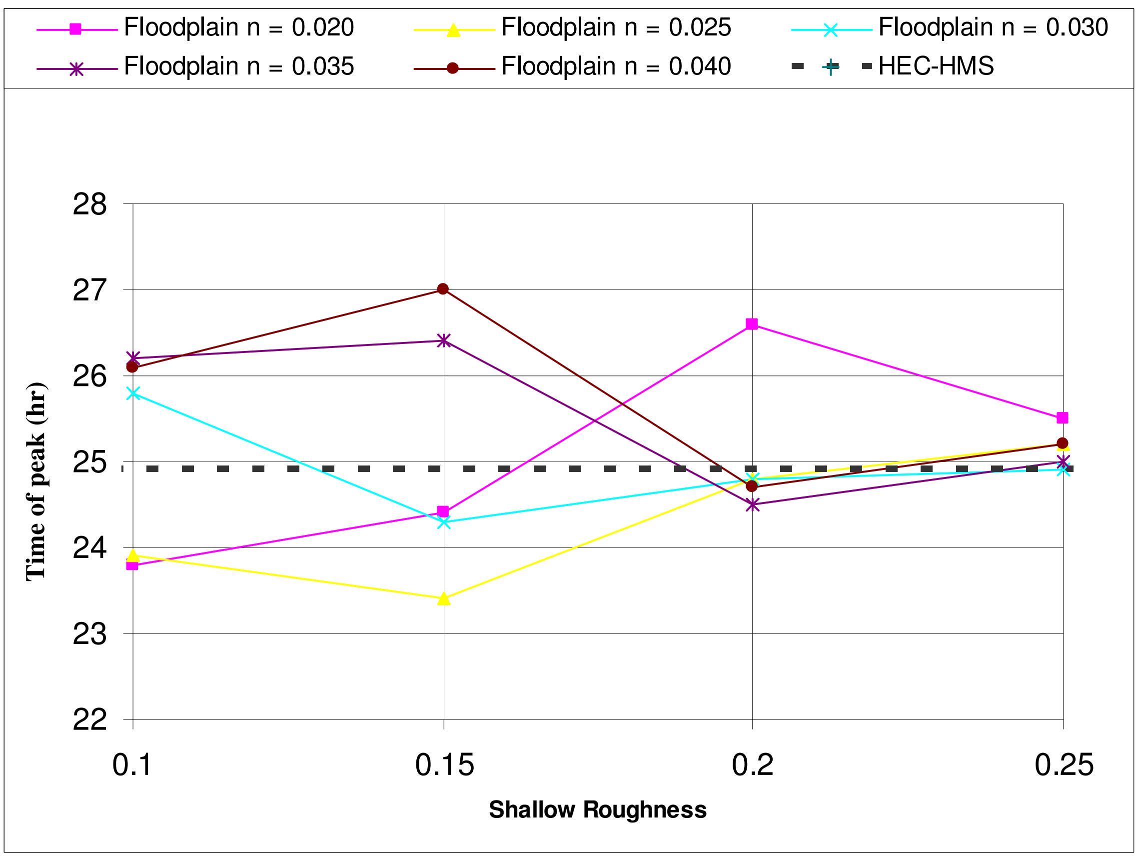

Figure E - 30 – Comparison of shallow roughness to predicted time of peak for Petty Ranch Models

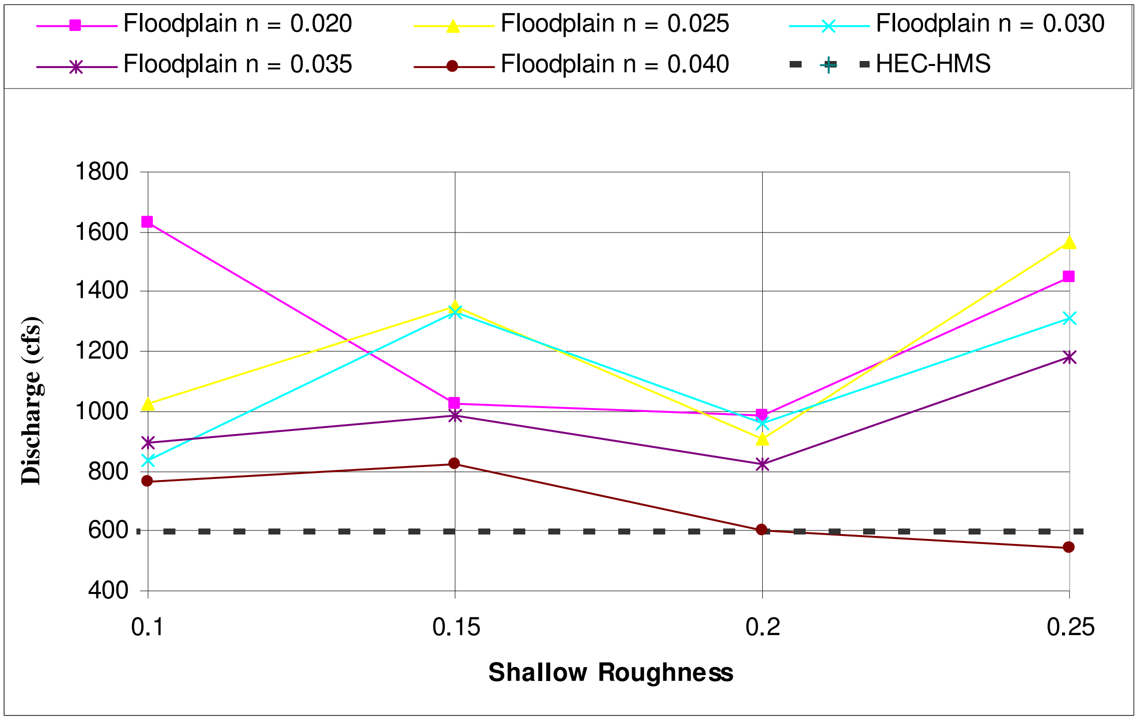

Figure E - 31 – Comparison of shallow roughness to predicted peak discharge for Franco Models

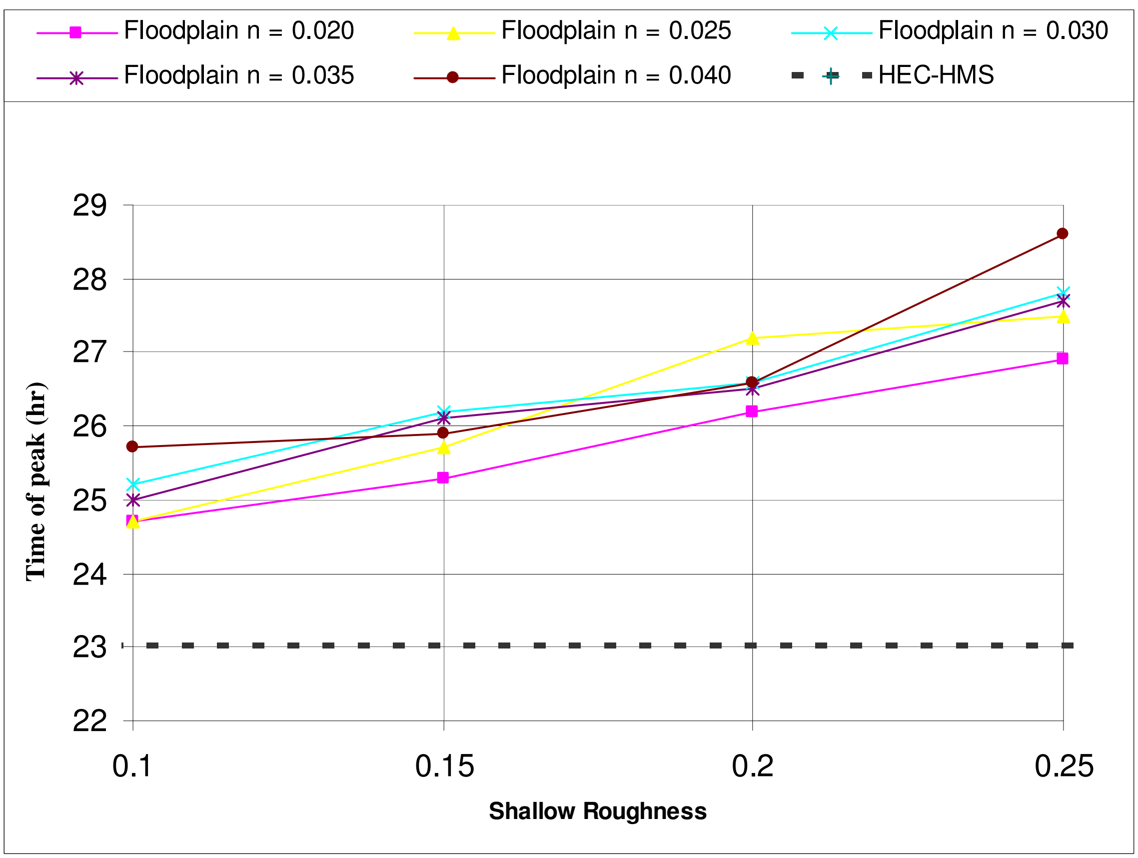

Figure E - 32 – Comparison of shallow roughness to predicted time of peak for Franco Models

The following figures compare grid size to predicted peak discharge and time of peak.

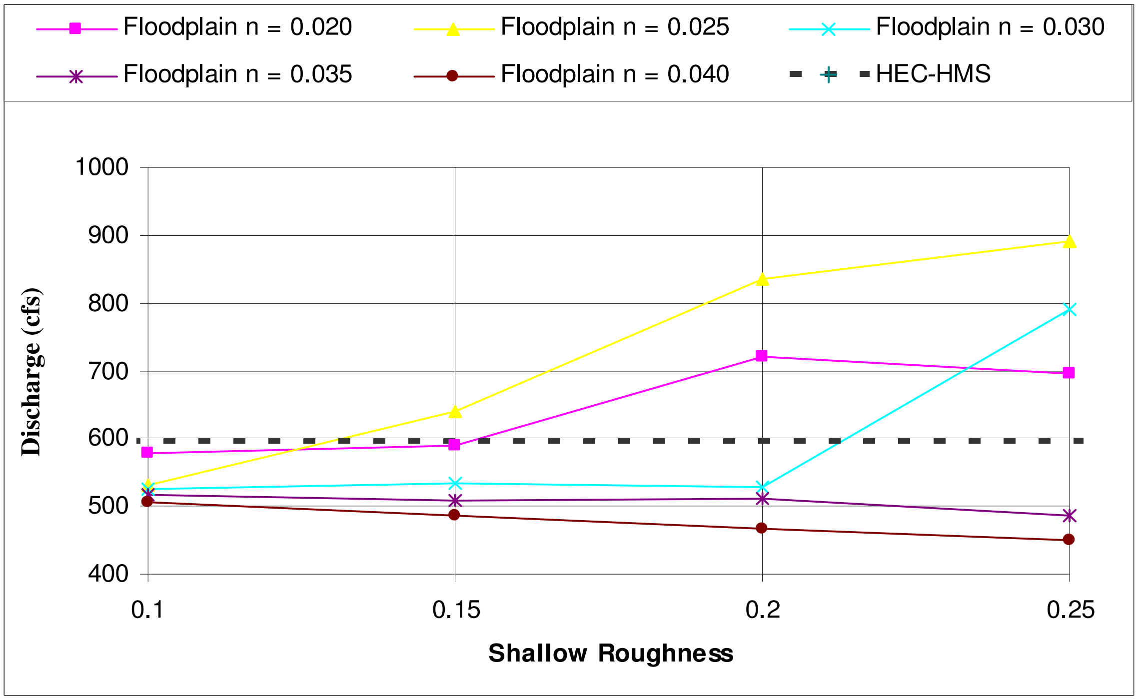

Figure E - 33 – Comparison of shallow roughness to predicted peak discharge for Cuprite Models

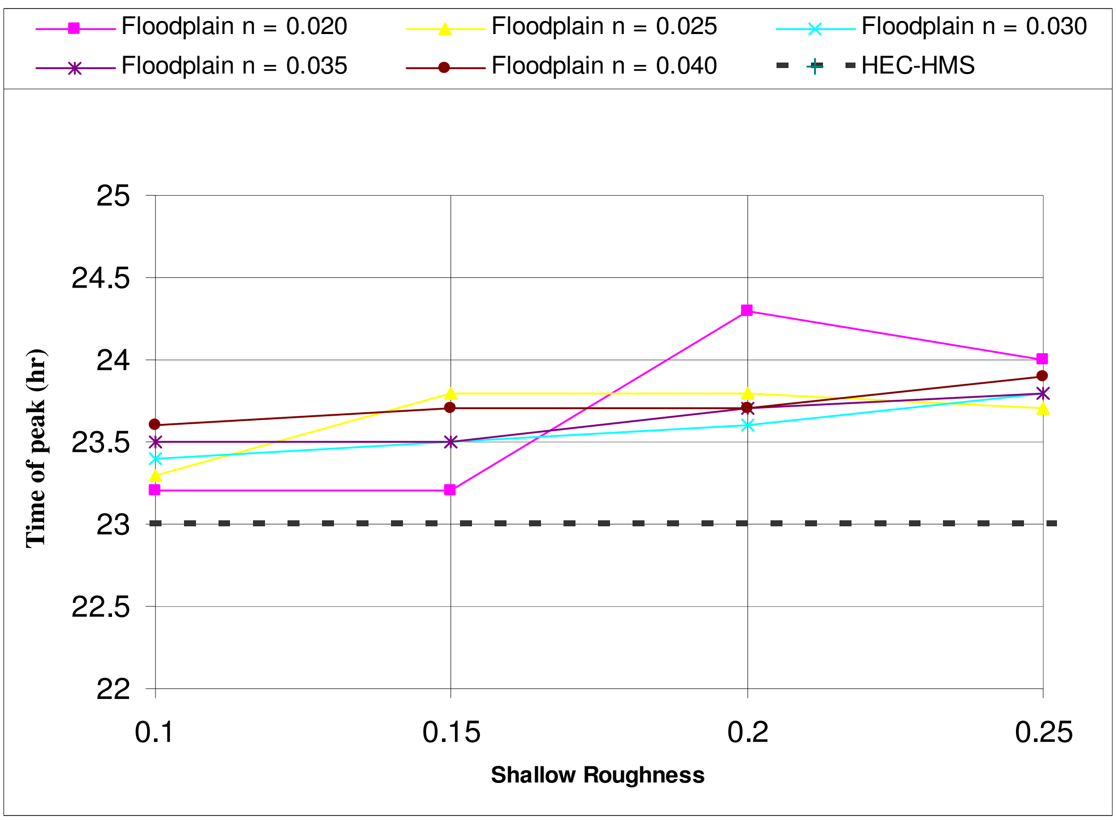

Figure E - 34 – Comparison of shallow roughness to predicted time of peak for Cuprite Models

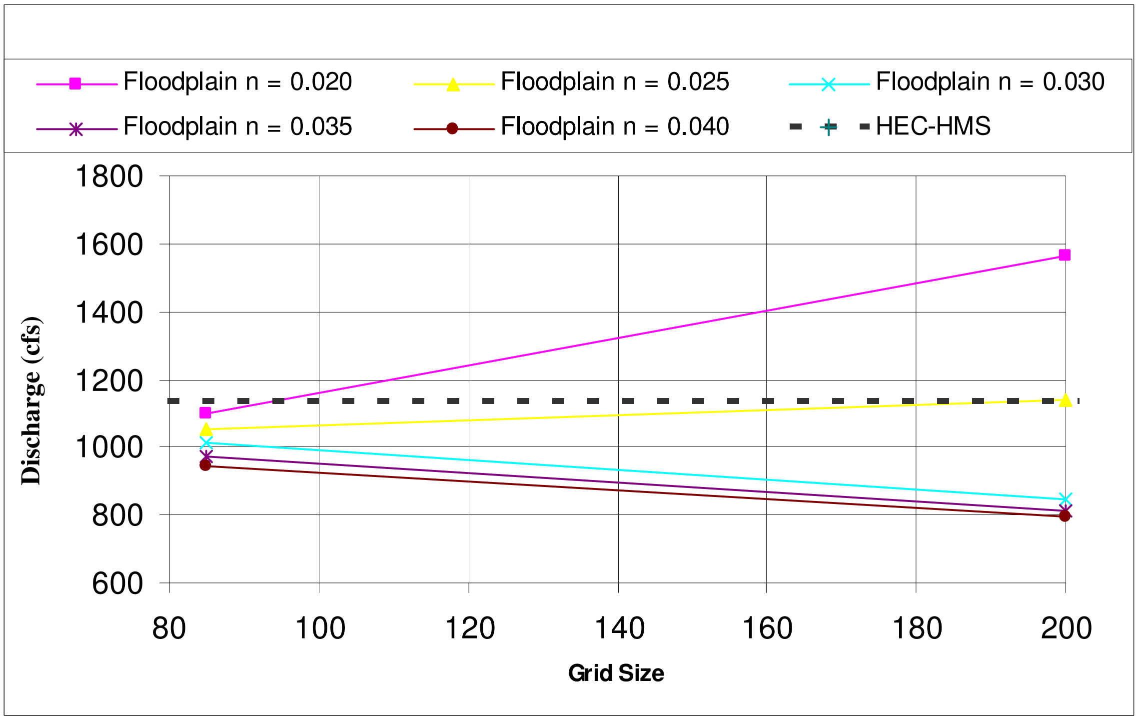

Figure E - 35 – Comparison of grid size to predicted peak discharge for Petty Ranch Models

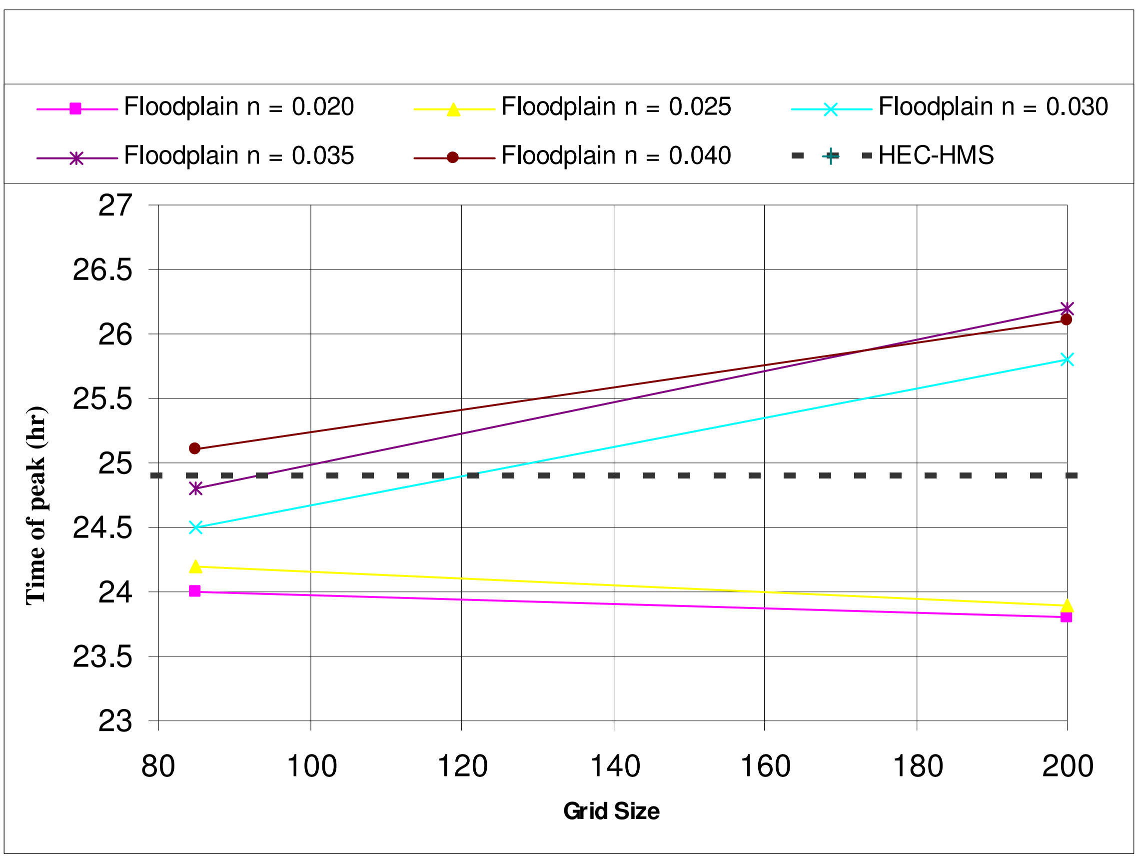

Figure E - 36 – Comparison of grid size to predicted time of peak for Petty Ranch Models

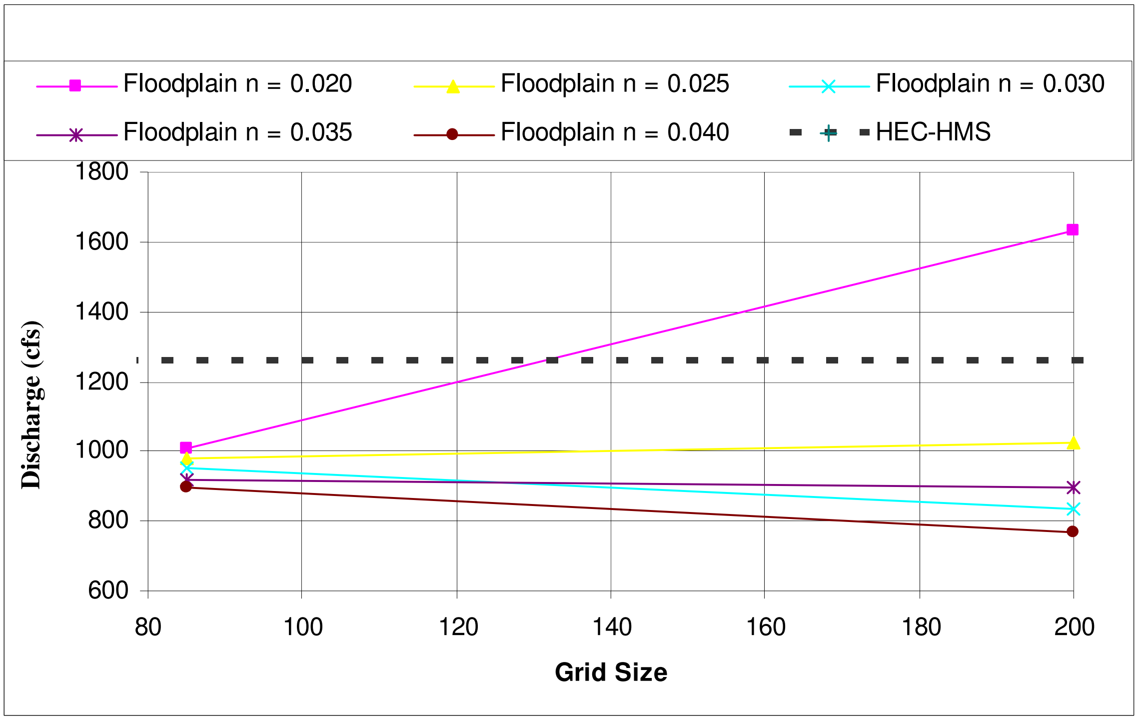

Figure E - 37 – Comparison of grid size to predicted peak discharge for Franco Models

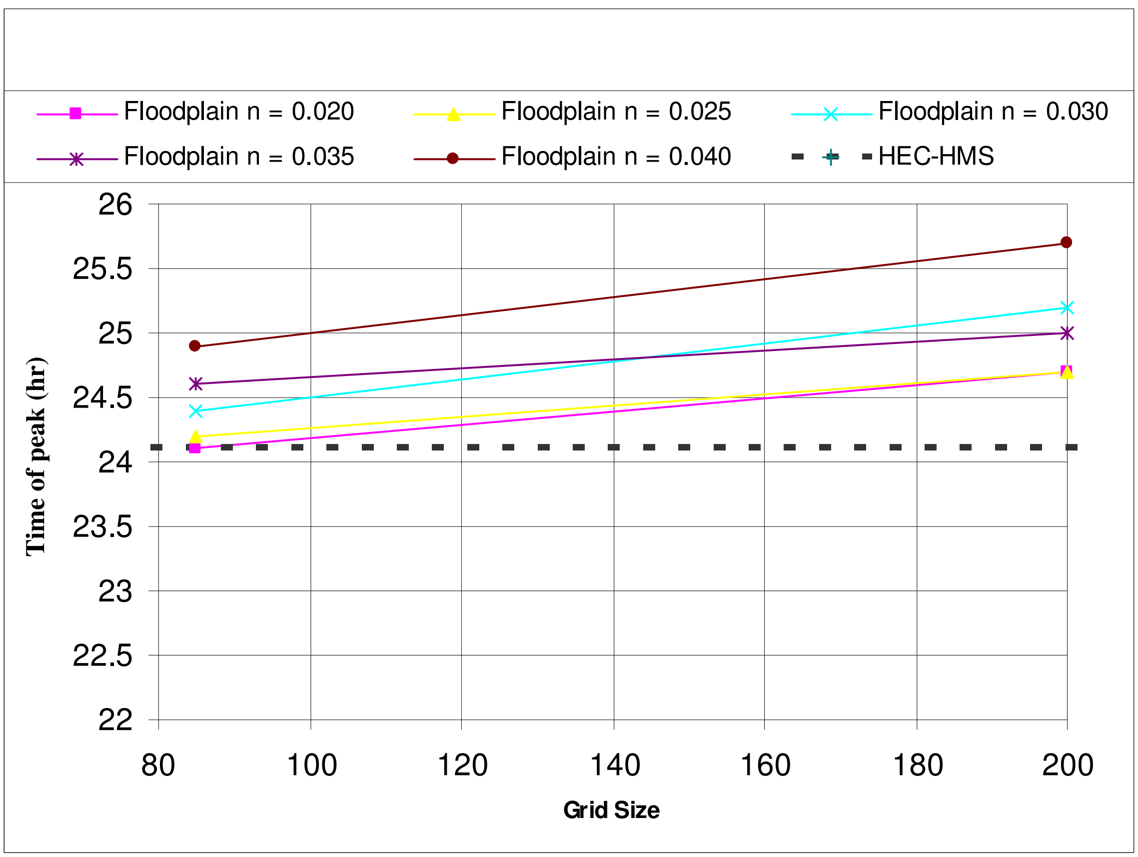

Figure E - 38 – Comparison of grid size to predicted time of peak for Franco Models

Figures E - 39 through E - 46 show scatter plots comparing floodplain roughness or shallow roughness to the ratio of the FLO-2D/HEC-HMS output. The time of peak ratio accounts for the time from the beginning of the rainfall, hour 12, and omits the first 12 hours. Figure E - 39 compares the discharge ratio to the floodplain roughness for all models (regardless of grid size or shallow roughness) with depth varied roughness turned off. Figure E - 40 compares the time of peak ratio for all models with depth varied roughness turned off. Figure E - 41 and Figure E - 42 provide similar comparisons for models with the depth varied roughness turned on.

Figure E - 43 through Figure E - 46 provide comparisons of the shallow roughness to the discharge or time of peak ratios for all models regardless of grid size or floodplain roughness. Note that the data is less complete in the figures showing the depth varied roughness turned off figures because it was determined early on in the calibration process that the depth varied roughness equation should be used for more consistent results.

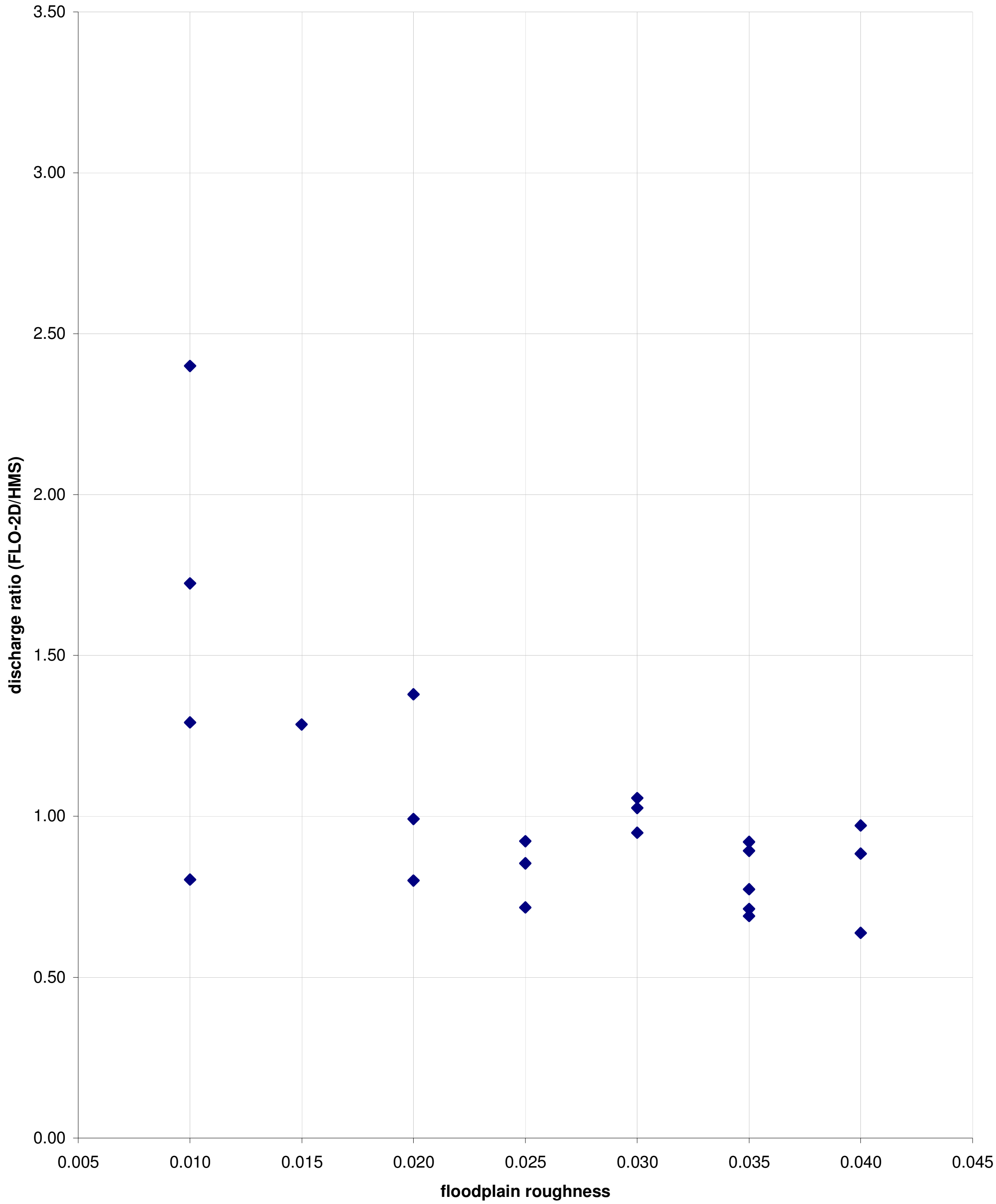

Figure E - 39 – Comparison of floodplain roughness to FLO-2D/HMS discharge ratio, DVR off

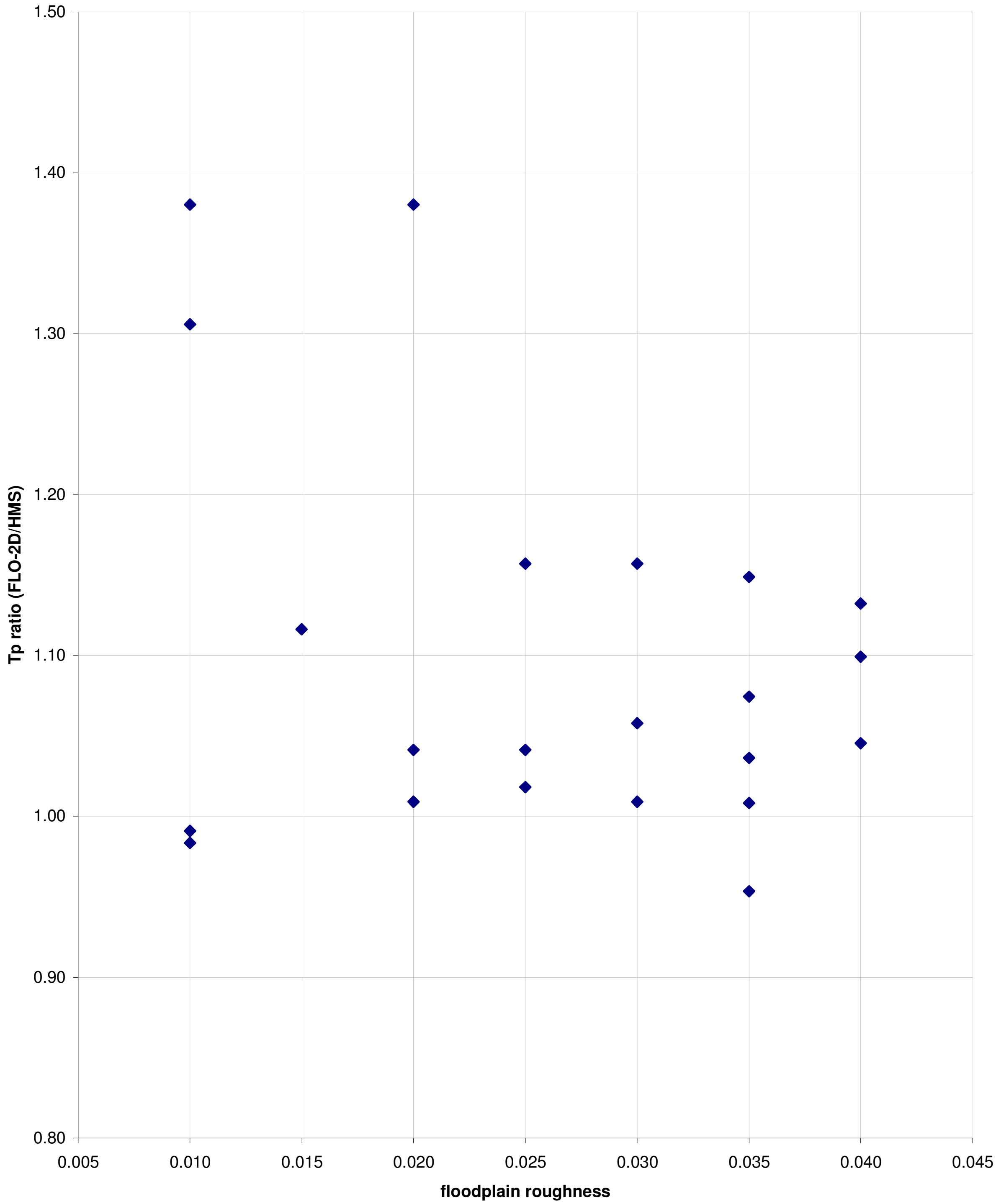

Figure E - 40 – Comparison of floodplain roughness to FLO-2D/HMS time to peak ratio, DVR off

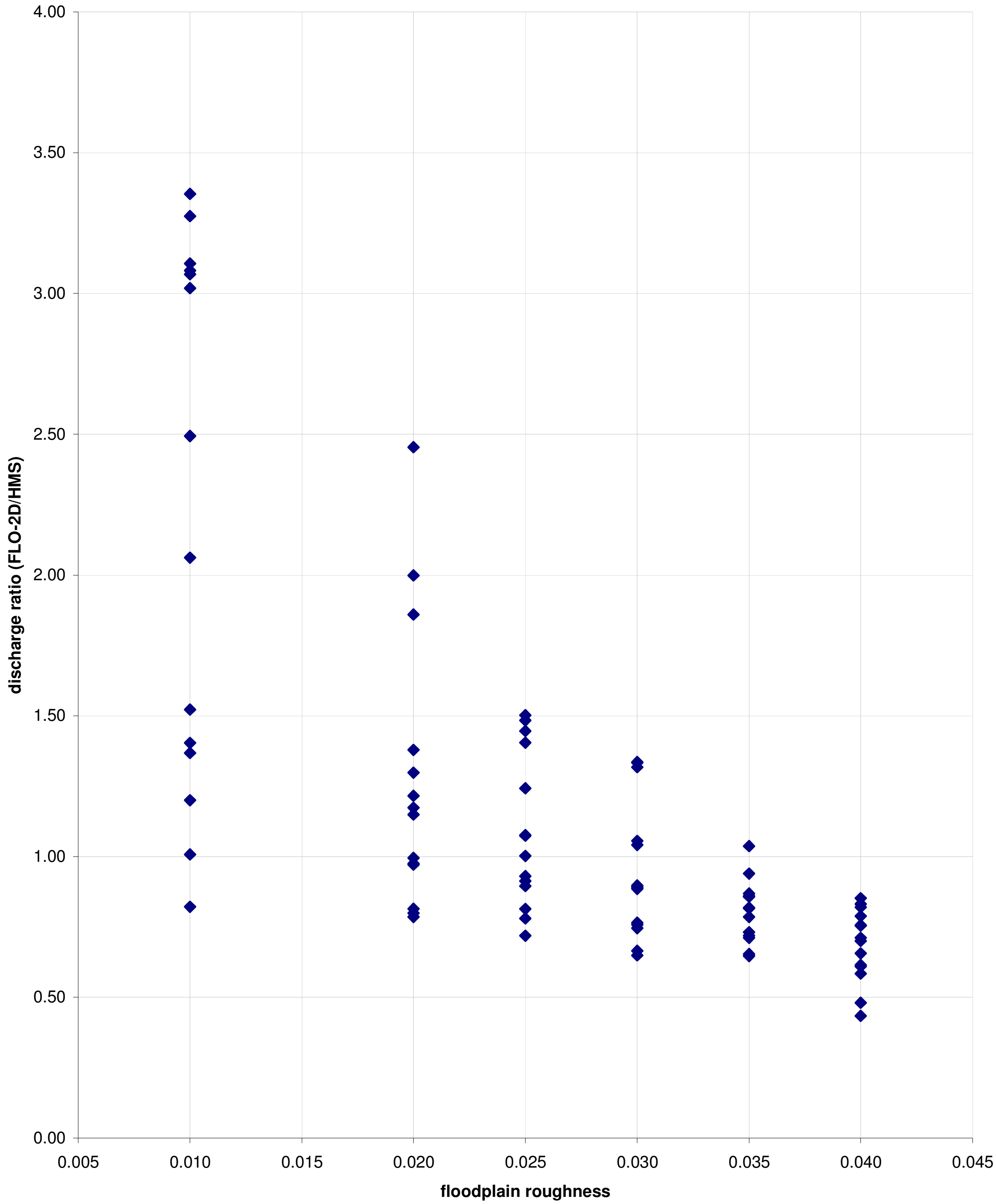

Figure E - 41 – Comparison of floodplain roughness to FLO-2D/HMS discharge ratio, DVR on

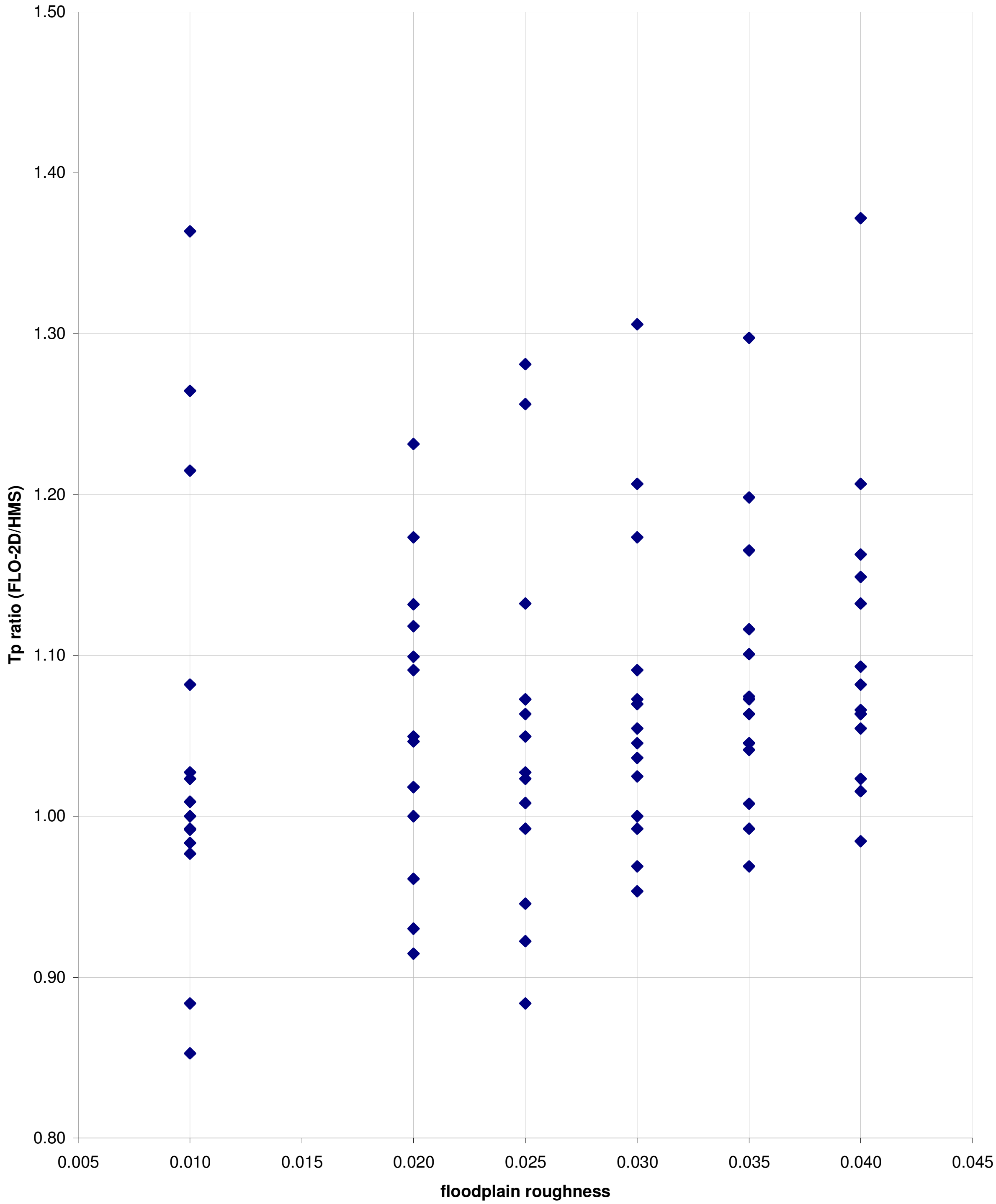

Figure E - 42 – Comparison of floodplain roughness to FLO-2D/HMS time to peak ratio, DVR on

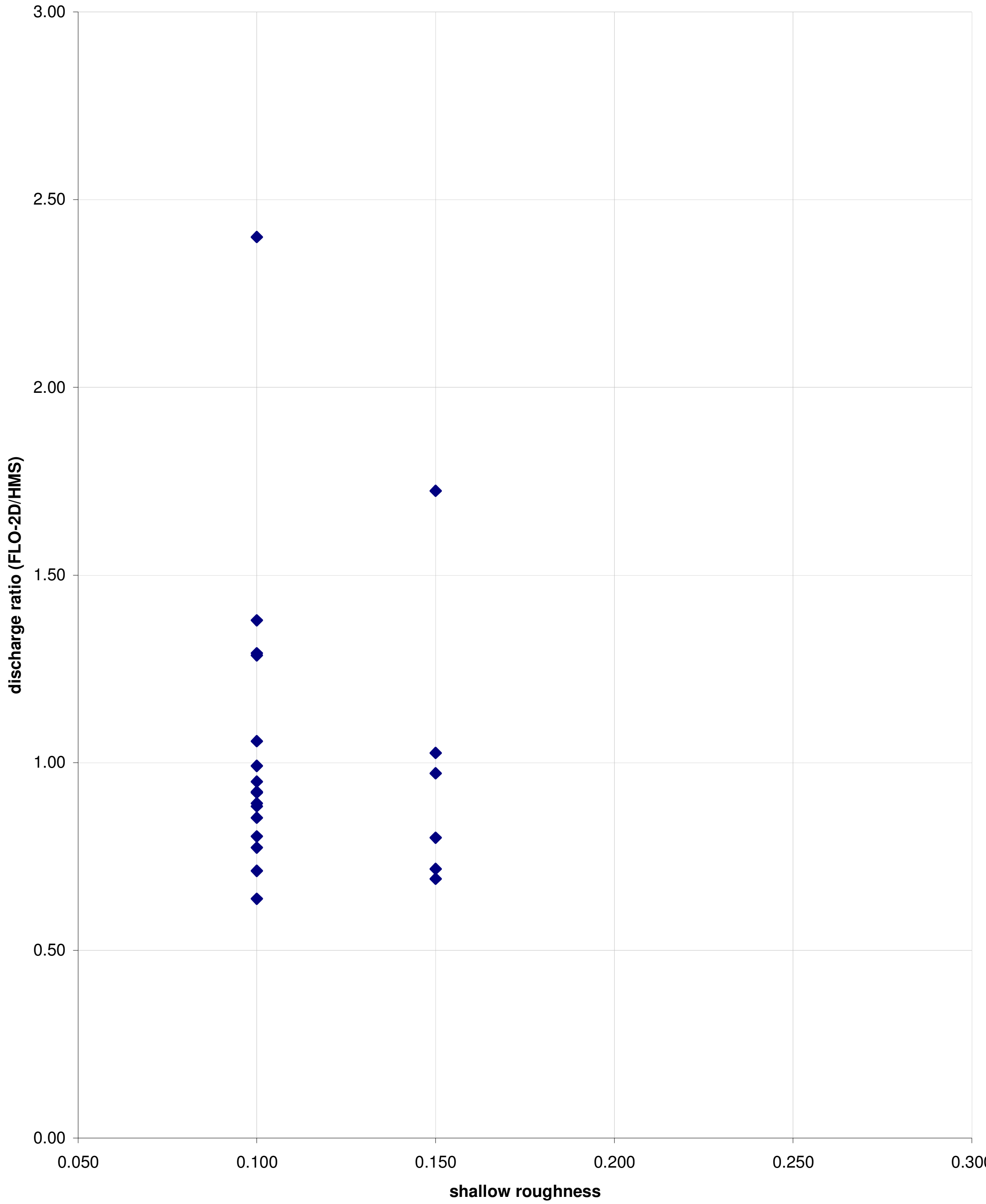

Figure E - 43 – Comparison of shallow roughness to FLO-2D/HMS discharge ratio, DVR off

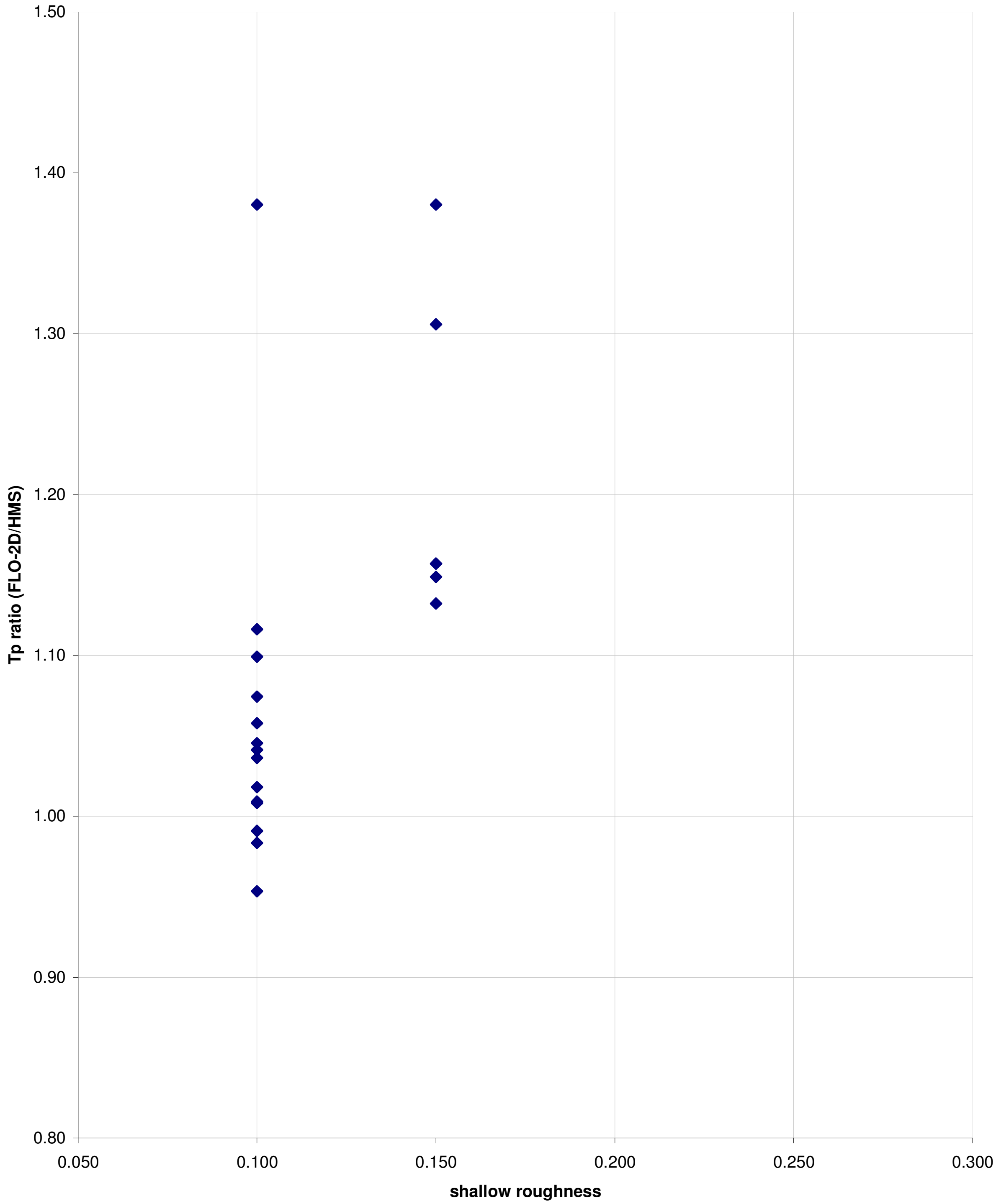

Figure E - 44 – Comparison of shallow roughness to FLO-2D/HMS time to peak ratio, DVR off

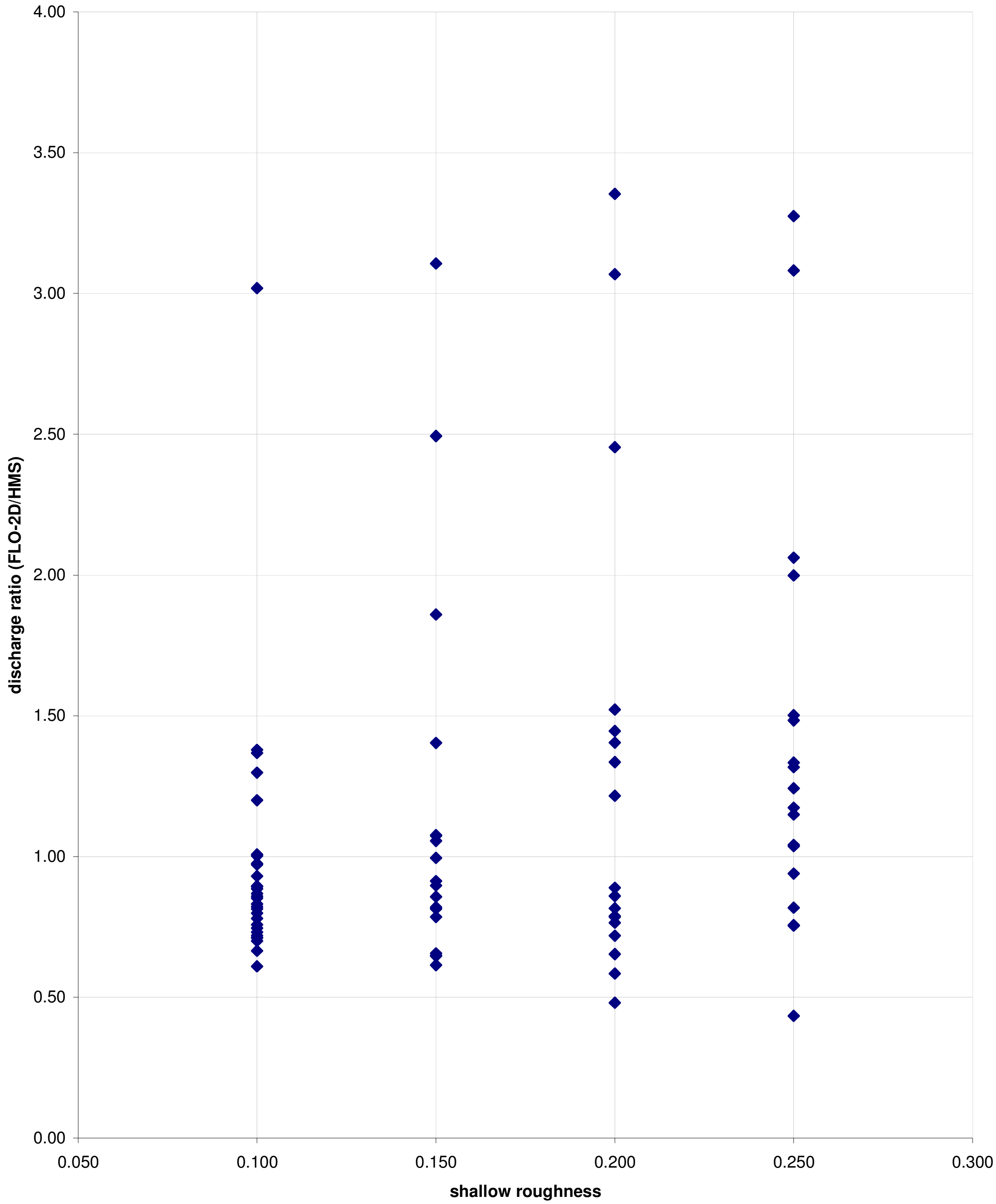

Figure E - 45 – Comparison of shallow roughness to FLO-2D/HMS discharge ratio, DVR on

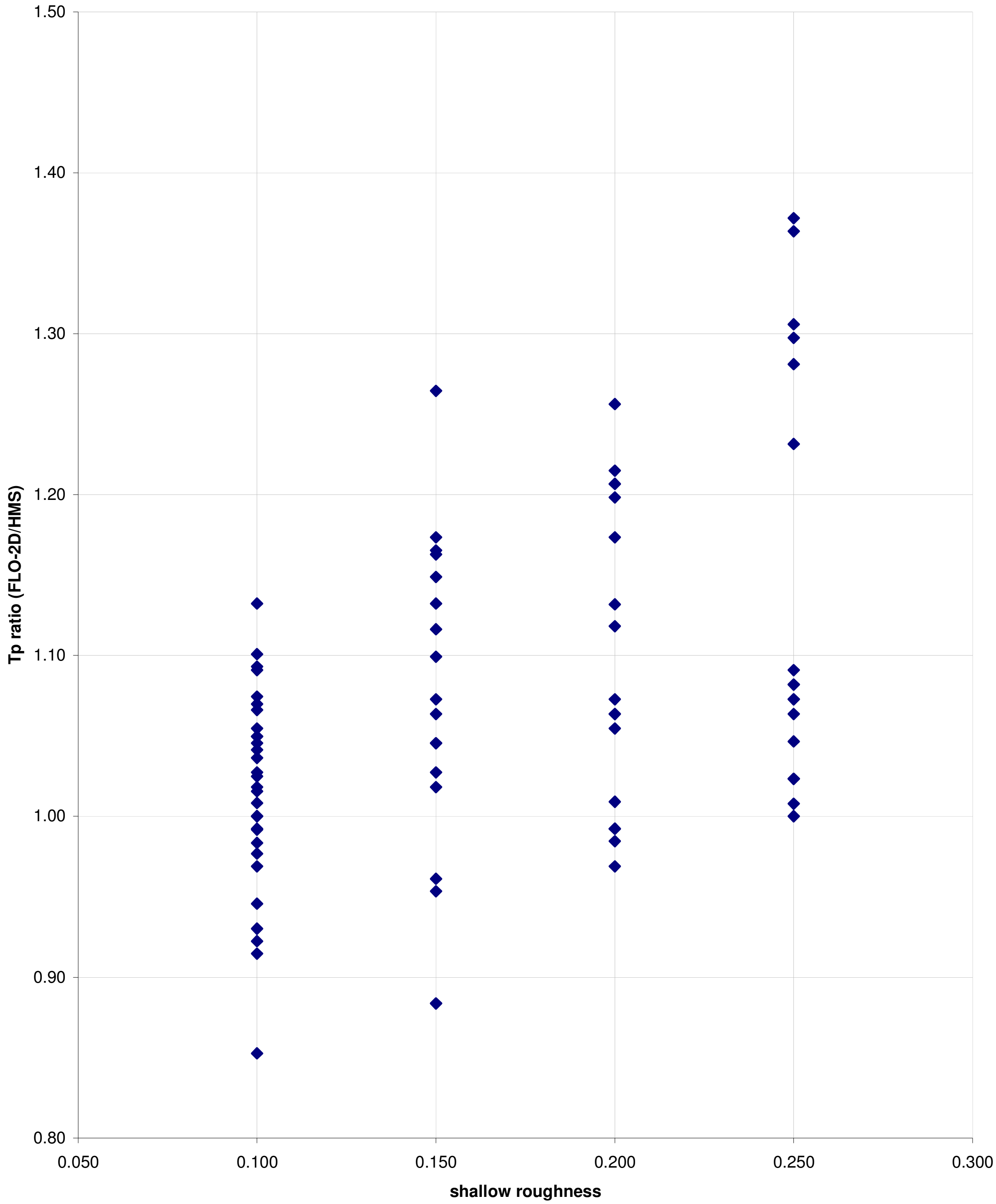

Figure E - 46 – Comparison of shallow roughness to FLO-2D/HMS time to peak ratio, DVR on

Table E - 16– Summary of calibration model results

Sub-model	Shallow Roughness	Floodplain roughness	Depth varied roughness	Q-100, 24-hour (cfs)	Ratio of FLO-2D Q to HMS Q	Time of peak (hr)	Ratio of FLO-2D Tp to HMS Tp (adjusted to hour 12)
CU1 - A	0.100	0.010	off	1396	2.40	22.9	0.99
CU1 - B	0.100	0.020	off	589	0.99	23.1	1.01
CU1 - C	0.100	0.025	off	548	0.92	23.2	1.02
CU1 - D	0.100	0.030	off	564	0.95	23.1	1.01
CU1 - E	0.100	0.035	off	530	0.89	23.4	1.04
CU1 - F	0.100	0.040	off	525	0.88	23.5	1.05
CU1 - G	0.100	0.010	on	686	1.20	23.0	1.00
CU1 - H	0.100	0.020	on	579	0.97	23.2	1.02
CU1 - I	0.100	0.025	on	532	0.90	23.3	1.03
CU1 - J	0.100	0.030	on	526	0.89	23.4	1.04
CU1 - K	0.100	0.035	on	516	0.87	23.5	1.05
CU1 - L	0.100	0.040	on	506	0.85	23.6	1.05
CU2 - A	0.150	0.010	on	1481	2.49	23.3	1.03
CU2 - B	0.150	0.020	on	591	0.99	23.2	1.02
CU2 - C	0.150	0.025	on	639	1.08	23.8	1.07
CU2 - D	0.150	0.030	on	533	0.90	23.5	1.05
CU2 - E	0.150	0.035	on	509	0.86	23.5	1.05
CU2 - F	0.150	0.040	on	487	0.82	23.7	1.06
CU3 - A	0.200	0.010	on	1992	3.35	23.1	1.01
CU3 - B	0.200	0.020	on	722	1.22	24.3	1.12
CU3 - C	0.200	0.025	on	834	1.40	23.8	1.07
CU3 - D	0.200	0.030	on	528	0.89	23.6	1.05
CU3 - E	0.200	0.035	on	511	0.86	23.7	1.06
CU3 - F	0.200	0.040	on	468	0.79	23.7	1.06
CU4 - A	0.250	0.010	on	1945	3.27	23.9	1.08
CU4 - B	0.250	0.020	on	697	1.17	24.0	1.09
CU4 - C	0.250	0.025	on	892	1.50	23.7	1.06
CU4 - D	0.250	0.030	on	792	1.33	23.8	1.07
CU4 - E	0.250	0.035	on	486	0.82	23.8	1.07
CU4 - F	0.250	0.040	on	449	0.76	23.9	1.08
FR1 - A	0.100	0.010	off	1011	0.80	23.9	0.98
FR1 - B	0.100	0.035	off	973	0.77	24.2	1.01
FR1 - C	0.100	0.010	on	1034	0.82	23.9	0.98
FR1 - D	0.100	0.020	on	1005	0.80	24.1	1.00
FR1 - E	0.100	0.025	on	981	0.78	24.2	1.01
FR1 - F	0.100	0.030	on	954	0.76	24.4	1.02

Table E - 16– Summary of calibration model results (continued)

Sub-model	Shallow Roughness	Floodplain roughness	Depth varied roughness	Q-100, 24-hour (cfs)	Ratio of FLO-2D Q to HMS Q	Time of peak (hr)	Ratio of FLO-2D Tp to HMS Tp (adjusted to hour 12)
FR1 - G	0.100	0.035	on	920	0.73	24.6	1.04
FR1 - H	0.100	0.040	on	894	0.71	24.9	1.07
FR2 - A	0.100	0.010	off	1625	1.29	28.7	1.38
FR2 - B	0.100	0.020	off	1735	1.38	24.6	1.04
FR2 - C	0.100	0.025	off	1074	0.85	24.6	1.04
FR2 - D	0.100	0.030	off	1330	1.06	24.8	1.06
FR2 - E	0.100	0.035	off	896	0.71	25.0	1.07
FR2 - F	0.100	0.040	off	802	0.64	25.3	1.10
FR2 - G	0.100	0.010	on	1268	1.01	24.0	0.99
FR2 - H	0.100	0.020	on	1633	1.30	24.7	1.05
FR2 - I	0.100	0.025	on	1024	0.81	24.7	1.05
FR2 - J	0.100	0.030	on	837	0.67	25.2	1.09
FR2 - K	0.100	0.035	on	894	0.71	25.0	1.07
FR2 - L	0.100	0.040	on	767	0.61	25.7	1.13
FR3 - A	0.150	0.010	off	2169	1.72	27.8	1.31
FR3 - B	0.150	0.020	off	1007	0.80	28.7	1.38
FR3 - C	0.150	0.025	off	902	0.72	26.0	1.16
FR3 - D	0.150	0.030	off	1291	1.03	26.0	1.16
FR3 - E	0.150	0.035	off	869	0.69	25.9	1.15
FR3 - F	0.150	0.040	off	1222	0.97	25.7	1.13
FR3 - G	0.150	0.010	on	1766	1.40	27.3	1.26
FR3 - H	0.150	0.020	on	1025	0.81	25.3	1.10
FR3 - I	0.150	0.025	on	1351	1.07	25.7	1.13
FR3 - J	0.150	0.030	on	1328	1.06	26.2	1.17
FR3 - K	0.150	0.035	on	988	0.79	26.1	1.17
FR3 - L	0.150	0.040	on	825	0.66	25.9	1.15
FR4 - A	0.200	0.010	on	1915	1.52	26.7	1.21
FR4 - B	0.200	0.020	on	988	0.79	26.2	1.17
FR4 - C	0.200	0.025	on	905	0.72	27.2	1.26
FR4 - D	0.200	0.030	on	963	0.77	26.6	1.21
FR4 - E	0.200	0.035	on	822	0.65	26.5	1.20
FR4 - F	0.200	0.040	on	605	0.48	26.6	1.21
FR5 - A	0.250	0.010	on	2,593	2.06	28.5	1.36
FR5 - B	0.250	0.020	on	1,446	1.15	26.9	1.23
FR5 - C	0.250	0.025	on	1,563	1.24	27.5	1.28
FR5 - D	0.250	0.030	on	1,310	1.04	27.8	1.31

Table E - 16– Summary of calibration model results (continued)

Sub-model	Shallow Roughness	Floodplain roughness	Depth varied roughness	Q-100, 24-hour (cfs)	Ratio of FLO-2D Q to HMS Q	Time of peak (hr)	Ratio of FLO-2D Tp to HMS Tp (adjusted to hour 12)
FR5 - E	0.250	0.035	on	1,182	0.94	27.7	1.30
FR5 - F	0.250	0.040	on	546	0.43	28.6	1.37
PR1 - A	0.100	0.015	off	1458	1.29	26.4	1.12
PR1 - B	0.100	0.035	off	1044	0.92	24.3	0.95
PR1 - C	0.100	0.005	on	2842	2.51	26.8	1.15
PR1 - D	0.100	0.010	on	1552	1.37	23.0	0.85
PR1 - E	0.100	0.020	on	1102	0.97	24.0	0.93
PR1 - F	0.100	0.025	on	1055	0.93	24.2	0.95
PR1 - G	0.100	0.030	on	1013	0.89	24.5	0.97
PR1 - H	0.100	0.035	on	974	0.86	24.8	0.99
PR1 - I	0.100	0.040	on	943	0.83	25.1	1.02
PR2 - A	0.100	0.010	on	3423	3.02	24.6	0.98
PR2 - B	0.100	0.020	on	1564	1.38	23.8	0.91
PR2 - C	0.100	0.025	on	1137	1.00	23.9	0.92
PR2 - D	0.100	0.030	on	846	0.75	25.8	1.07
PR2 - E	0.100	0.035	on	815	0.72	26.2	1.10
PR2 - F	0.100	0.040	on	794	0.70	26.1	1.09
PR3 - A	0.150	0.010	on	3523	3.11	23.4	0.88
PR3 - B	0.150	0.020	on	2109	1.86	24.4	0.96
PR3 - C	0.150	0.025	on	1035	0.91	23.4	0.88
PR3 - D	0.150	0.030	on	736	0.65	24.3	0.95
PR3 - E	0.150	0.035	on	733	0.65	26.4	1.12
PR3 - F	0.150	0.040	on	697	0.61	27.0	1.16
PR4 - A	0.200	0.010	on	3480	3.07	24.8	0.99
PR4 - B	0.200	0.020	on	2783	2.45	26.6	1.13
PR4 - C	0.200	0.025	on	1640	1.45	24.8	0.99
PR4 - D	0.200	0.030	on	1514	1.34	24.8	0.99
PR4 - E	0.200	0.035	on	926	0.82	24.5	0.97
PR4 - F	0.200	0.040	on	663	0.58	24.7	0.98
PR5 - A	0.250	0.010	on	3495	3.08	25.2	1.02
PR5 - B	0.250	0.020	on	2266	2.00	25.5	1.05
PR5 - C	0.250	0.025	on	1682	1.48	25.2	1.02
PR5 - D	0.250	0.030	on	1494	1.32	24.9	1.00
PR5 - E	0.250	0.035	on	1176	1.04	25.0	1.01
PR5 - F	0.250	0.040	on	856	0.75	25.2	1.02

E.3 Large-Scale Model Variations

Several variations of the large-scale model have been developed following the calibration routine. The purpose of this exercise is to quantify the effects of changing assorted variables.

Table E - 17 summarizes the variable input for 10 models of the entire basin on a 400-foot grid. A total of 377 flow recording cross sections were cut for each model with the average discharge for these sections recorded in Table E - 17.

Table E - 17 - Summary of 400-foot Grid Input Parameters

Model	Floodplain roughness		Shallow roughness	DVR	Average Discharge for 377 Cross Sections
	Piedmont areas	Hillslope areas			
A	0.035	0.053	0.10	off	1,052
B	0.035	0.053	0.15	off	952
C	0.035	0.053	0.20	off	910
D	0.035	0.053	0.25	off	931
E	0.035	0.053	0.10	on	1,064
F	0.035	0.053	0.15	on	918
G	0.035	0.053	0.20	on	833
H	0.035	0.053	0.25	on	807
I	0.030	0.040	0.10	on	1,075
J	0.030	0.040	0.15	on	930

The peak discharges at several key locations have been compared. Figure E - 47 shows the locations of these flow recording cross sections. The peak discharges recorded at these cross sections, for models E through J, have been listed in Table E - 18. Note that the trends shown for models E through H are similar to those for models A through D.

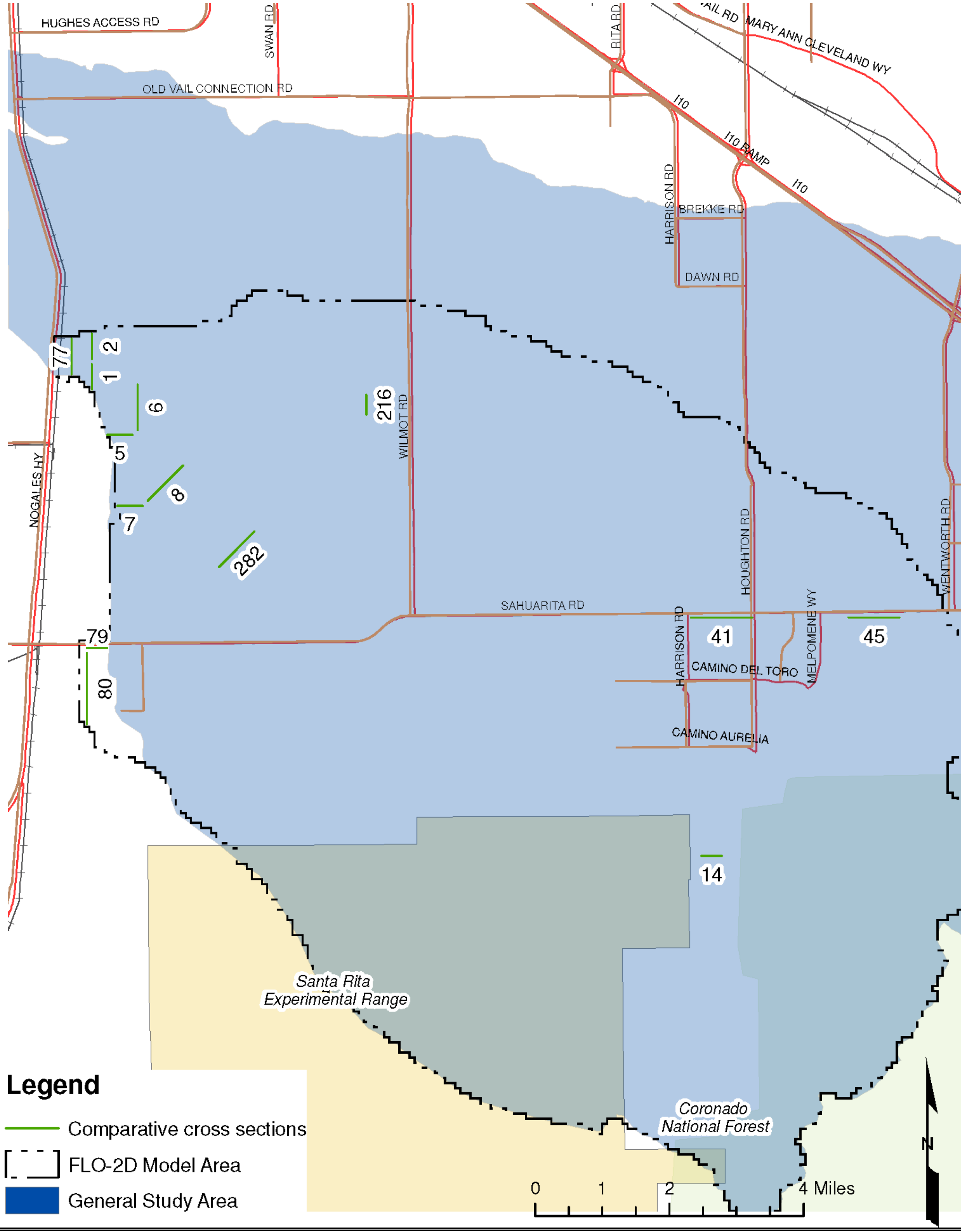

Figure E - 47 - Location map of comparative flow recording cross sections

(numbers shown are cross section numbers)

Table E - 18 - Peak Discharges from 400-foot Large-Scale Model Variations

Cross Section	Model / Shallow roughness value					
	E	F	G	H	I	J
	0.10	0.15	0.20	0.25	0.10	0.15
1	14,832	11,892	10,168	9,004	14,791	11,805
2	962	985	1,003	1,027	989	1,007
5	7,337	5,807	4,967	4,364	7,163	5,728
6	7,807	6,227	5,294	4,771	7,806	6,312
7	2,606	2,197	2,000	1,726	2,621	2,242
8	5,024	4,000	4,514	4,304	4,974	3,923
14	4,278	3,575	3,202	3,043	4,112	3,525
41	1,022	827	747	648	1,033	850
45	849	651	544	615	844	651
77	15,371	12,810	10,928	9,645	15,341	12,724
79	188	158	153	152	189	158
80	1,472	1,237	1,120	1,072	1,502	1,250
216	2,275	1,715	1,465	1,251	2,247	1,689
282	3,238	3,705	4,064	4,009	3,437	4,241

The results summarized above indicate that changing the shallow roughness coefficient can have a considerable impact, especially on the most downstream cross sections. A change from 0.10 to 0.15 has the effect of decreasing the discharge at the lowest cross section by over 2,500 cfs or 16 percent. The results also indicate that lowering the floodplain roughness coefficient from 0.035 on the piedmont to 0.030 and from 0.053 on the hillslopes to 0.040 has a less significant impact on the predicted peak discharge values.

A couple of observations should be pointed out. First, cross sections 2 and 282 both predict greater discharges with increasing shallow roughness, contrary to the trend observed in the other cross sections. Second, if the depth varied roughness is turned off, the peak discharge in cross section 282 is 3,526 cfs in Model A and over 6,600 cfs in Model D.

A 200-foot grid model was also developed. The peak discharges (at key locations) and flow depths were compared between the 200-foot grid and 400-foot grid models. With shallow roughness of 0.10 and floodplain roughness of 0.030 on the piedmont and 0.040 on the hillslopes, the ultimate discharge at the outfall of the model is 16,531 cfs for the 200-foot grid model and 15,371 cfs for the 400-foot grid model. The following table compares the flow depths predicted by the 200-foot and 400-foot grid models with the above mentioned roughness values.

Table E - 19 - Comparison of Predicted Flow Depths – 200-foot and 400-foot Grids

Threshold Depth (ft)	400-ft grid model		200-ft grid model	
	Percent above threshold	Area (sq mi) above threshold	Percent above threshold	Area (sq mi) above threshold
0.03	94.9%	119.6	87.9%	111.5
0.2	55.5%	70.0	48.9%	62.0
0.5	9.5%	12.0	9.5%	12.0
1	2.6%	3.3	2.3%	2.9
2	0.9%	1.2	0.8%	1.0

The above table is useful in determining a threshold depth for delineating the flood limits.

Appendix F - Verification of Volume Conservation

F Verification of Volume Conservation

This appendix is included to account for the flow volume within the study area.

F.1 Routing Diagram

The following diagrams show how the 7 sub-models are connected along with inflow and outflow points and volumes for the 3-hour storm and the 24-hour storm.

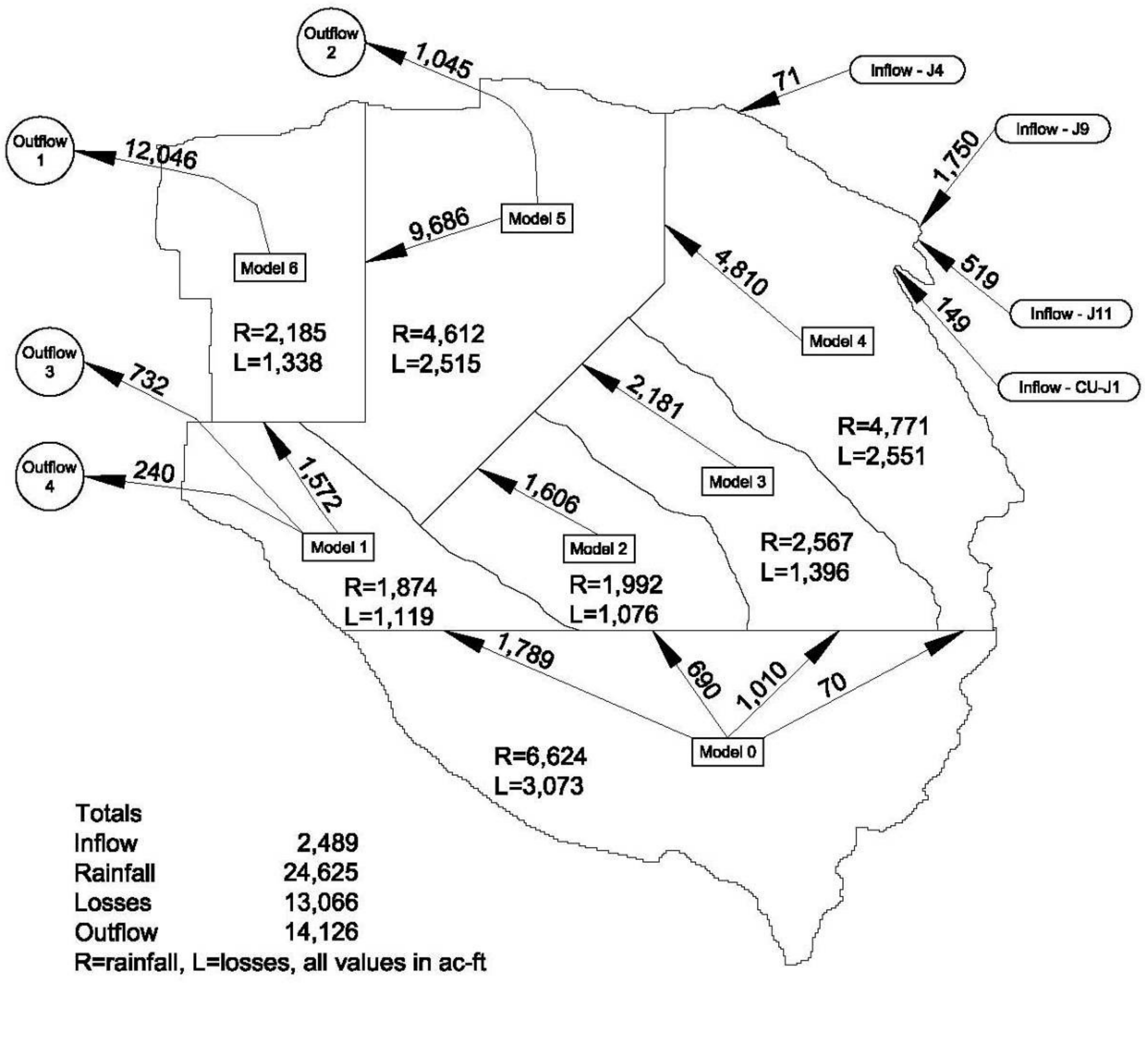

Figure F - 1 - FLO-2D 100-year, 3-hour Sub-model routing diagram

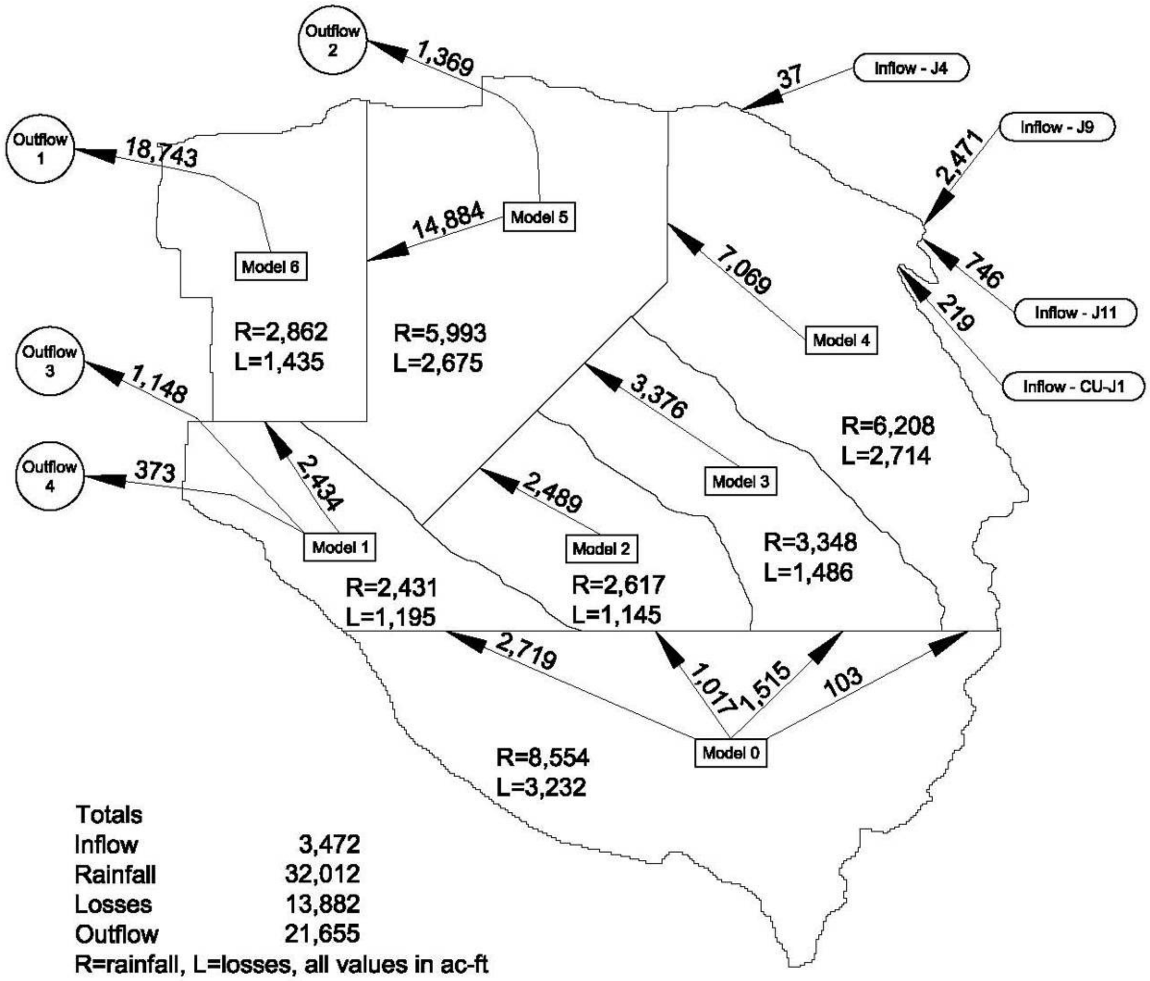

Figure F - 2 - FLO-2D 100-year, 24-hour Sub-model routing diagram

The following table summarizes the inflow, outflow, and rainfall for each of the models.

Table F - 1 - Volume summaries for FLO-2D sub-models

	Model Name	**0**	
	Geometry		
	Grid element spacing (ft)		200
	Elevation data source		USGS DEM
	Number of elements - total		23,430
	Number of elements - outflow		285
	Number of elements net		23,145
	Area (sq mi) net		33.21
	Average CN		86.3
	Rainfall and runoff (in)	**3-hr**	**24-hr**
a	Precipitation depth*	3.74	4.83
b	Infiltration and Interception*	1.38	1.47
c	Runoff (a-b)	2.36	3.36
	Inflow volume (ac-ft)	**3-hr**	**24-hr**
d	Rainfall*	6,624	8,554
e	Total inflow hydrograph*	0	0
f	Rainfall and inflow (d+e)	6,624	8,554
	Loss volume (ac-ft)	**3-hr**	**24-hr**
g	Infiltration and Interception*	2,441	2,602
h	Storage*	631	630
i	Total loss (g+h)	3,073	3,232
	Outflow volume (ac-ft)	**3-hr**	**24-hr**
j	Total outflow*	3,551	5,322
j1	*Outflow to Model 1***	*1,789*	*2,719*
j2	*Outflow to Model 2***	*690*	*1,017*
j3	*Outflow to Model 3***	*1,010*	*1,515*
j4	*Outflow to Model 4***	*70*	*103*

Note * - Values recorded directly by FLO-2D SUMMARY.DAT file
Note ** - Values are those recorded by downstream model, some volume error occurs due to rounding errors

	Model Name	**1**	
	Geometry		
	Grid element spacing (ft)		100
	Elevation data source		PAG
	Number of elements - total		30,440
	Number of elements - outflow		111
	Number of elements net		30,329
	Area (sq mi) net		10.88
	Average CN		83.8
	Rainfall and runoff (in)	**3-hr**	**24-hr**
a	Precipitation depth*	3.23	4.19
b	Infiltration and Interception*	1.54	1.67
c	Runoff (a-b)	1.69	2.52
	Inflow volume (ac-ft)	**3-hr**	**24-hr**
d	Rainfall*	1,874	2,431
e	Total inflow hydrograph*	1,789	2,719
e1	*Inflow from Model 0*	*1,789*	*2,719*
f	Rainfall and inflow (d+e)	3,663	5,150
	Loss volume (ac-ft)	**3-hr**	**24-hr**
g	Infiltration and Interception*	889	965
h	Storage*	230	230
i	Total loss (g+h)	1,119	1,195
	Outflow volume (ac-ft)	**3-hr**	**24-hr**
j	Total outflow*	2,544	3,955
j1	*Outflow to Model 5*	*1,572*	*2,434*
j2	*Outflow 3***	*732*	*1,148*
j3	*Outflow 4****	*240*	*373*

Note * - Values recorded directly by FLO-2D SUMMARY.DAT file
Note ** - Recorded by CS 1-001
Note *** - Recorded by CS 1-002

	Model Name		2
	Geometry		
	Grid element spacing (ft)		100
	Elevation data source		PAG
	Number of elements - total		31,184
	Number of elements - outflow		100
	Number of elements net		31,084
	Area (sq mi) net		11.15
	Average CN		85.1
	Rainfall and runoff (in)	**3-hr**	**24-hr**
a	Precipitation depth*	3.35	4.40
b	Infiltration and Interception*	1.45	1.57
c	Runoff (a-b)	1.90	2.83
	Inflow volume (ac-ft)	**3-hr**	**24-hr**
d	Rainfall*	1,992	2,617
e	Total inflow hydrograph*	690	1,017
e1	*Inflow from Model 0*	*690*	*1,017*
f	Rainfall and inflow (d+e)	2,682	3,634
	Loss volume (ac-ft)	**3-hr**	**24-hr**
g	Infiltration and Interception*	863	933
h	Storage*	213	213
i	Total loss (g+h)	1,076	1,145
	Outflow volume (ac-ft)	**3-hr**	**24-hr**
j	Total outflow*	1,606	2,489
j1	*Outflow to Model 5*	*1,606*	*2,489*

Note * - Values recorded directly by FLO-2D SUMMARY.DAT file

	Model Name		3
	Geometry		
	Grid element spacing (ft)		100
	Elevation data source		PAG
	Number of elements - total		38,970
	Number of elements - outflow		82
	Number of elements net		38,888
	Area (sq mi) net		13.95
	Average CN		84.4
	Rainfall and runoff (in)	**3-hr**	**24-hr**
a	Precipitation depth*	3.45	4.50
b	Infiltration and Interception*	1.52	1.64
c	Runoff (a-b)	1.93	2.86
	Inflow volume (ac-ft)	**3-hr**	**24-hr**
d	Rainfall*	2,567	3,348
e	Total inflow hydrograph*	1,010	1,515
e1	*Inflow from Model 0*	*1,010*	*1,515*
f	Rainfall and inflow (d+e)	3,576	4,862
	Loss volume (ac-ft)	**3-hr**	**24-hr**
g	Infiltration and Interception*	1,128	1,219
h	Storage*	268	267
i	Total loss (g+h)	1,396	1,486
	Outflow volume (ac-ft)	**3-hr**	**24-hr**
j	Total outflow*	2,181	3,376
j1	*Outflow to Model 5*	*2,181*	*3,376*

Note * - Values recorded directly by FLO-2D SUMMARY.DAT file

Model Name		4	
Geometry			
Grid element spacing (ft)			100
Elevation data source			PAG
Number of elements - total			73,102
Number of elements - outflow			178
Number of elements net			55,965
Area (sq mi) net			26.16
Average CN			84.9
	Rainfall and runoff (in)	**3-hr**	**24-hr**
a	Precipitation depth*	3.42	4.45
b	Infiltration and Interception*	1.47	1.59
c	Runoff (a-b)	1.95	2.86
	Inflow volume (ac-ft)	**3-hr**	**24-hr**
d	Rainfall*	4,771	6,208
e	Total inflow hydrograph*	2,290	3,575
e1	*Inflow from Model 0*	*70*	*103*
e2	*Inflow from Stantec J9*	*1,750*	*2,471*
e3	*Inflow from Stantec J11*	*519*	*746*
e4	*Inflow from Stantec CU-J1*	*149*	*219*
e5	*Inflow from J4 flow split*	*71*	*37*
f	Rainfall and inflow (d+e)	7,361	9,783
	Loss volume (ac-ft)	**3-hr**	**24-hr**
g	Infiltration and Interception*	2,049	2,213
h	Storage*	502	501
i	Total loss (g+h)	2,551	2,714
	Outflow volume (ac-ft)	**3-hr**	**24-hr**
j	Total outflow*	4,810	7,069
j1	*Outflow to Model 5*	*4,810*	*7,069*

Note * - Values recorded directly by FLO-2D SUMMARY.DAT file

Model Name		5	
Geometry			
Grid element spacing (ft)			100
Elevation data source			PAG
Number of elements - total			74,768
Number of elements - outflow			357
Number of elements net			74,411
Area (sq mi) net			26.69
Average CN			85.4
	Rainfall and runoff (in)	**3-hr**	**24-hr**
a	Precipitation depth*	3.24	4.21
b	Infiltration and Interception*	1.41	1.52
c	Runoff (a-b)	1.83	2.69
	Inflow volume (ac-ft)	**3-hr**	**24-hr**
d	Rainfall*	4,612	5,993
e	Total inflow hydrograph*	8,635	12,936
e1	*Inflow from Model 2*	*1,606*	*2,489*
e2	*Inflow from Model 3*	*2,181*	*3,376*
e3	*Inflow from Model 4*	*4,810*	*7,069*
f	Rainfall and inflow (d+e)	13,247	18,929
	Loss volume (ac-ft)	**3-hr**	**24-hr**
g	Infiltration and Interception*	1,999	2,159
h	Storage*	516	516
i	Total loss (g+h)	2,515	2,675
	Outflow volume (ac-ft)	**3-hr**	**24-hr**
j	Total outflow*	10,731	16,253
j1	*Outflow to Model 6*	*9,686*	*14,884*
j2	*Outflow 2***	*1,045*	*1,369*

Note * - Values recorded directly by FLO-2D SUMMARY.DAT file
Note ** - Recorded by CS 5-199

	Model Name	6	
	Geometry		
	Grid element spacing (ft)		100
	Elevation data source		PAG
	Number of elements - total		39,853
	Number of elements - outflow		4
	Number of elements net		39,849
	Area (sq mi) net		14.29
	Average CN		85.1
	Rainfall and runoff (in)	**3-hr**	**24-hr**
a	Precipitation depth*	2.87	3.76
b	Infiltration and Interception*	1.37	1.50
c	Runoff (a-b)	1.50	2.26
	Inflow volume (ac-ft)	**3-hr**	**24-hr**
d	Rainfall*	2,185	2,862
e	Total inflow hydrograph*	11,250	17,318
e1	*Inflow from Model 1*	*1,572*	*2,434*
e2	*Inflow from Model 5*	*9,686*	*14,884*
f	Rainfall and inflow (d+e)	13,435	20,180
	Loss volume (ac-ft)	**3-hr**	**24-hr**
g	Infiltration and Interception*	1,032	1,126
h	Storage*	306	309
i	Total loss (g+h)	1,338	1,435
	Outflow volume (ac-ft)	**3-hr**	**24-hr**
j	Total outflow*	12,046	18,743
j1	*Outflow 1***	*12,109*	*18,765*

Note * - Values recorded directly by FLO-2D SUMMARY.DAT file
Note ** - Recorded by CS 6-001

	Model Name	Combination	
	Geometry		
	Grid element spacing (ft)		n/a
	Elevation data source		n/a
	Number of elements - total		294,788
	Number of elements - outflow		1,117
	Number of elements net		293,671
	Area (sq mi) net		136
	Average CN		85.2
	Inflow volume (ac-ft)	**3-hr**	**24-hr**
d	Rainfall*	24,625	30,012
e	Total inflow hydrograph (e1+e2+e3+e4)	2,489	3,472
e1	*Inflow from Stantec J9*	*1,750*	*2,471*
e2	*Inflow from Stantec J11*	*519*	*746*
e3	*Inflow from Stantec CU-J1*	*149*	*219*
e4	*Inflow from J4 flow split*	*71*	*37*
f	Rainfall and inflow (d+e)	27,114	35,485
	Loss volume (ac-ft)	**3-hr**	**24-hr**
g	Infiltration and Interception*	10,401	11,216
h	Storage*	2,666	2,666
i	Total loss (g+h)	13,066	13,882
	Outflow volume (ac-ft)	**3-hr**	**24-hr**
j	Total outflow	14,126	21,655
j1	*Outflow 1*	*12,109*	*18,765*
j2	*Outflow 2*	*1,045*	*1,369*
j3	*Outflow 3*	*732*	*1,148*
j4	*Outflow 4*	*240*	*373*

Appendix G - Comparison of FLO-2D and HEC-HMS Results

Table G - 1 - Verification of sub-basin characteristics

Model Number	Test Area	Area (sq mi)	CN	Precip. (in) p100-3 / p100-24	Sheet flow L (ft) / S (ft/ft)	Shallow flow L (ft) / S (ft/ft)	Chan. flow L (ft) / v (fps)	T-lag (min)
1	1-1	0.813	88.57	3.74 / 4.83	100 / 0.2	1840 / 0.41	9310 / 8	22
2	1-2	2.869	87.69	3.74 / 4.83	100 / 0.1	1700 / 0.42	13655 / 3.2	38
3	2-2A	0.489	86.14	3.35 / 4.40	100 / 0.036	2090 / 0.046	12310 / 6	34
4	2-2B	0.970	86.20	3.37 / 4.43	100 / 0.041	1940 / 0.052	19340 / 5.9	45
5	J2-2	1.459	N/A	3.36 / 4.41	N/A / N/A	N/A / N/A	N/A / N/A	N/A
6	2-2C	0.067	83.00	3.35 / 4.40	100 / 0.03	600 / 0.03	2365 / 1.6	23
7	2-3A	0.219	86.33	3.35 / 4.40	100 / 0.03	970 / 0.009	5085 / 4	27
8	2-3A&B	1.747	86.10	3.35 / 4.40	100 / 0.03	850 / 0.058	18550 / 4	56
9	2-4A	0.074	79.00	3.28 / 4.27	100 / 0.021	1380 / 0.021	3080 / 1.4	35
10	2-4B	0.113	79.00	3.31 / 4.30	100 / 0.02	1240 / 0.02	3725 / 1.5	38
11	2-4C	0.088	79.00	3.36 / 4.41	100 / 0.025	890 / 0.025	2960 / 2.8	20
12	2-5	0.056	83.00	3.35 / 4.40	100 / 0.023	2180 / 0.025	1984 / 0.023	26
13	3-1	7.760	89.52	3.74 / 4.83	100 / 0.33	1400 / 0.44	24960 / 5.5	50
14	4-1	0.800	88.26	3.47 / 4.53	100 / 0.57	1200 / 0.52	11210 / 8	19

Table G - 1 - Verification of sub-basin characteristics (continued)

Model Number	Test Area	Area (sq mi)	CN	Precip. (in) p100-3 / p100-24	Sheet flow L (ft) / S (ft/ft)	Shallow flow L (ft) / S (ft/ft)	Chan. flow L (ft) / v (fps)	T-lag (min)
15	4-2	0.511	85.66	3.45 / 4.50	100 / 0.54	1100 / 0.48	7225 / 11	13
16	4-3	0.590	88.72	3.46 / 4.51	100 / 0.3	1110 / 0.045	9980 / 15	16
17	J4-4	1.725	86.26	3.45 / 4.50	N/A / N/A	N/A / N/A	N/A / N/A	N/A
18	5-1	1.625	87.31	3.52 / 4.58	100 / 0.43	380 / 0.05	3220 / 7	31
19	5-2	0.643	80.68	3.42 / 4.45	100 / 0.43	930 / 0.5	10130 / 5.4	24
20	5-3	0.116	80.19	3.45 / 4.50	100 / 0.43	900 / 0.5	17730 / 6	19
21	6-1	0.936	83.70	3.42 / 4.45	100 / 0.47	600 / 0.51	8490 / 8	17
22	7-1	1.034	85.03	3.45 / 4.45	100 / 0.47	850 / 0.51	12370 / 4.8	31
23	7-2	0.668	87.70	3.45 / 4.45	100 / 0.58	640 / 0.5	9270 / 5.9	21
24	Stantec FL-J9	14.390	N/A		N/A / N/A	N/A / N/A	N/A / N/A	N/A
25	Stantec FL-J11	4.640	N/A		N/A / N/A	N/A / N/A	N/A / N/A	N/A
26	Stantec CU-J1	1.470	N/A		N/A / N/A	N/A / N/A	N/A / N/A	N/A
27	Stantec FR-J2	11.050	N/A		N/A / N/A	N/A / N/A	N/A / N/A	N/A
28	Stantec FR-J4	3.700	N/A		N/A / N/A	N/A / N/A	N/A / N/A	N/A

Table G - 2 - Verification of sub-basin FLO-2D results

Model Number	Test Area	CS Label	Storm	Q (cfs)	T (hr)	V (ac-ft)	q* (cfs/sq mi)	Q-ratio	T-ratio
1	1-1	0-068	3-hour	1721	1.88	83	2117	3.1	0.18
			24-hour	564	10.42	121	694		
2	1-2	0-067	3-hour	4083	2.12	348	1423	2.0	0.20
			24-hour	2093	10.49	516	730		
3	2-2A	2-110	3-hour	374	2.13	42	765	1.8	0.20
			24-hour	211	10.54	66	431		
4	2-2B	2-109	3-hour	552	2.56	84	569	1.6	0.23
			24-hour	339	11.21	133	349		
5	J2-2	2-044	3-hour	824	2.44	125	565	1.7	0.22
			24-hour	497	11.06	200	341		
6	2-2C	2-108	3-hour	58	1.81	6	866	2.1	0.18
			24-hour	28	10.26	10	418		
7	2-3A	2-074	3-hour	368	1.80	20	1680	1.8	0.18
			24-hour	202	10.15	31	922		
8	2-3A&B	2-075	3-hour	924	2.62	154	529	1.5	0.23
			24-hour	602	11.18	246	345		
9	2-4A	5-213	3-hour	34	2.25	10	459	1.4	0.10
			24-hour	25	22.76	17	338		
10	2-4B	5-212	3-hour	56	2.35	13	496	1.8	0.10
			24-hour	32	22.82	20	283		
11	2-4C	2-282	3-hour	86	1.54	7	977	1.7	0.15
			24-hour	50	10.26	12	568		
12	2-5	2-217	3-hour	50	1.89	5	893	1.9	0.18
			24-hour	26	10.41	8	464		
13	3-1	3-041	3-hour	6957	2.26	888	897	1.6	0.21
			24-hour	4346	11.00	1344	560		
14	4-1	3-153	3-hour	2679	1.85	85	3349	4.2	0.18
			24-hour	635	10.23	127	794		

* Assumes the FLO-2D drainage area is equal to that delineated for HEC-HMS

Table G - 2 - Verification of sub-basin FLO-2D results (continued)

Model Number	Test Area	CS Label	Storm	Q (cfs)	T (hr)	V (ac-ft)	q* (cfs/sq mi)	Q-ratio	T-ratio
15	4-2	3-235	3-hour	915	1.83	47	1791	2.5	0.18
			24-hour	365	10.23	72	714		
16	4-3	3-238	3-hour	1259	1.82	68	2134	2.6	0.18
			24-hour	481	10.25	100	815		
17	J4-4	3-231	3-hour	2181	2.08	158	1264	2.2	0.20
			24-hour	992	10.58	241	575		
18	5-1	4-010	3-hour	2416	2.03	166	1487	2.1	0.20
			24-hour	1177	10.32	251	724		
19	5-2	4-011	3-hour	712	2.05	45	1107	2.4	0.19
			24-hour	299	10.54	74	465		
20	5-3	3-152	3-hour	134	1.93	10	1155	2.2	0.19
			24-hour	61	10.23	16	526		
21	6-1	4-174	3-hour	954	1.99	80	1019	2.0	0.19
			24-hour	467	10.42	125	499		
22	7-1	4-124	3-hour	1019	1.94	91	985	2.1	0.18
			24-hour	497	10.51	140	481		
23	7-2	4-130	3-hour	933	2.08	70	1397	2.2	0.20
			24-hour	431	10.50	107	645		
24	Stantec FL-J9	N/A	3-hour	N/A	N/A	N/A	N/A	N/A	N/A
			24-hour	N/A	N/A	N/A	N/A		
25	Stantec FL-J11	N/A	3-hour	N/A	N/A	N/A	N/A	N/A	N/A
			24-hour	N/A	N/A	N/A	N/A		
26	Stantec CU-J1	N/A	3-hour	N/A	N/A	N/A	N/A	N/A	N/A
			24-hour	N/A	N/A	N/A	N/A		
27	Stantec FR-J2	N/A	3-hour	N/A	N/A	N/A	N/A	N/A	N/A
			24-hour	N/A	N/A	N/A	N/A		
28	Stantec FR-J4	N/A	3-hour	N/A	N/A	N/A	N/A	N/A	N/A
			24-hour	N/A	N/A	N/A	N/A		

* Assumes the FLO-2D drainage area is equal to that delineated for HEC-HMS

Table G - 3 - Verification of sub-basin HEC-HMS results

Model Number	Test Area	Storm	Q (cfs)	T (hr)	V (ac-ft)	q (cfs/sq mi)	Q-ratio	T-ratio
1	1-1	3-hour	1607	1.83	110	1977	2.3	0.18
		24-hour	697	10.17	155	857		
2	1-2	3-hour	3748	2.17	377	1306	2.0	0.21
		24-hour	1875	10.50	532	654		
3	2-2A	3-hour	555	2.08	76	1135	2.0	0.20
		24-hour	282	10.42	52	577		
4	2-2B	3-hour	908	2.25	153	936	1.8	0.21
		24-hour	491	10.58	104	506		
5	J2-2	3-hour	1423	2.17	155	975	1.9	0.21
		24-hour	757	10.50	229	519		
6	2-2C	3-hour	86	1.83	6	1284	2.2	0.18
		24-hour	40	10.25	9	597		
7	2-3A	3-hour	294	1.92	23	1342	2.1	0.19
		24-hour	141	10.25	34	644		
8	2-3A&B	3-hour	1385	2.50	186	793	1.8	0.23
		24-hour	785	10.83	274	449		
9	2-4A	3-hour	57	2.08	6	770	1.9	0.20
		24-hour	30	10.42	9	405		
10	2-4B	3-hour	83	2.17	9	735	1.9	0.21
		24-hour	44	10.50	13	389		
11	2-4C	3-hour	103	1.83	7	1170	2.1	0.18
		24-hour	48	10.17	11	545		
12	2-5	3-hour	67	1.92	5	1196	2.1	0.19
		24-hour	32	10.25	8	571		
13	3-1	3-hour	8893	2.33	1088	1146	1.9	0.22
		24-hour	4660	10.67	1516	601		
14	4-1	3-hour	1518	1.75	97	1898	2.3	0.17
		24-hour	655	10.17	139	819		

Table G - 3 - Verification of sub-basin HEC-HMS results (continued)

Model Number	Test Area	Storm	Q (cfs)	T (hr)	V (ac-ft)	q (cfs/sq mi)	Q-ratio	T-ratio
15	4-2	3-hour	1078	1.67	55	2110	2.5	0.17
		24-hour	423	10.08	81	828		
16	4-3	3-hour	1271	1.75	72	2154	2.5	0.17
		24-hour	515	10.08	103	873		
17	J4-4	3-hour	2679	1.83	199	1553	2.2	0.18
		24-hour	1207	10.25	285	700		
18	5-1	3-hour	2226	2.00	193	1370	2.1	0.19
		24-hour	1079	10.33	278	664		
19	5-2	3-hour	748	1.92	56	1163	2.1	0.19
		24-hour	354	10.25	85	551		
20	5-3	3-hour	214	1.67	10	1845	2.7	0.17
		24-hour	80	10.08	15	690		
21	6-1	3-hour	1559	1.75	92	1666	2.4	0.17
		24-hour	655	10.08	137	700		
22	7-1	3-hour	1250	2.00	109	1209	2.1	0.19
		24-hour	607	10.33	158	587		
23	7-2	3-hour	1171	1.83	78	1753	2.3	0.18
		24-hour	509	10.17	111	762		
24	Stantec FL-J9	3-hour	7400	2.30	1537	514	1.28	0.20
		24-hour	5772	11.70	2471	401		
25	Stantec FL-J11	3-hour	2330	2.00	453	502	1.27	0.18
		24-hour	1840	11.30	746	397		
26	Stantec CU-J1	3-hour	1022	1.40	148	695	1.49	0.13
		24-hour	684	10.90	219	465		
27	Stantec FR-J2	3-hour	3231	3.50	1031	292	1.19	0.27
		24-hour	2712	13.00	1704	245		
28	Stantec FR-J4	3-hour	1601	2.58	361	433	1.25	0.22
		24-hour	1282	11.90	592	346		

Appendix H - Plates and Exhibits

Plate 1 - Northern Flow Splits

Plate 2 - FLO-2D Predicted 10-year and 100-year Flood Limits with Significant Flow Paths and Concentration Points

Exhibit 1 - Velocity and Depth Maps